ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

1991

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

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INTRODUCTION

The U. S. Water Conservation Laboratory (USWCL) Annual Research Report is intended to inform upper level management within the Agricultural Research Service, other ARS research locations involved in natural resources research, and our many collaborators and cooperators about progress on our research projects in 1991 and plans for 1992. It is our intent to keep the individual reports short but informative, focusing on what is being done and why, specific objectives of the research, the approach to the problem, brief results, what it all means, future plans for the project, and cooperators involved. We want to make sure it is clear what the product of the research will be (or is) and how it contributes to water conservation.

The overall mission of the U. S. Water Conservation Laboratory is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts focus on irrigation systems efficiency; management of irrigation systems; methods for scheduling irrigations; remote sensing of crop, soil, and atmospheric conditions; practices for protection of groundwater from agricultural chemicals; introduction of new crops; and the effect of future increases of atmospheric CO_2 on climate and associated yields and water requirements of agricultural crops.

The USWCL program is structured into two Research Units: Irrigation and Water Quality (I & WQ) and Environmental and Plant Dynamics (E & PD). I & WQ focuses on water management with emphasis on irrigation and water quality; E & PD concentrates on carbon dioxide-climate change, germplasm development for new crops, and remote sensing. Drs. Bert Clemmens and Bruce Kimball are the Research Leaders for the respective Research Units. The organizational structure for the USWCL is shown as Figure 1, and the entire USWCL personnel list as Table 1.

The mission of the Irrigation and Water Quality Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit uses holistic approaches to develop concepts and tools for improving the design, operation, and management of both farm irrigation systems and irrigation water delivery systems. In particular, this includes developing best management practices for water and chemical applications, characterizing the movement and degradation of agricultural chemicals below irrigated fields, developing water measurement and control structures, and integrating farm and irrigation project operations and management. The research consists of field research studies, laboratory studies, and mathematical/computer modeling. Technology transfer efforts focus on management improvement processes in which users actively participate, thereby expediting acceptance, and on user-friendly computer software.

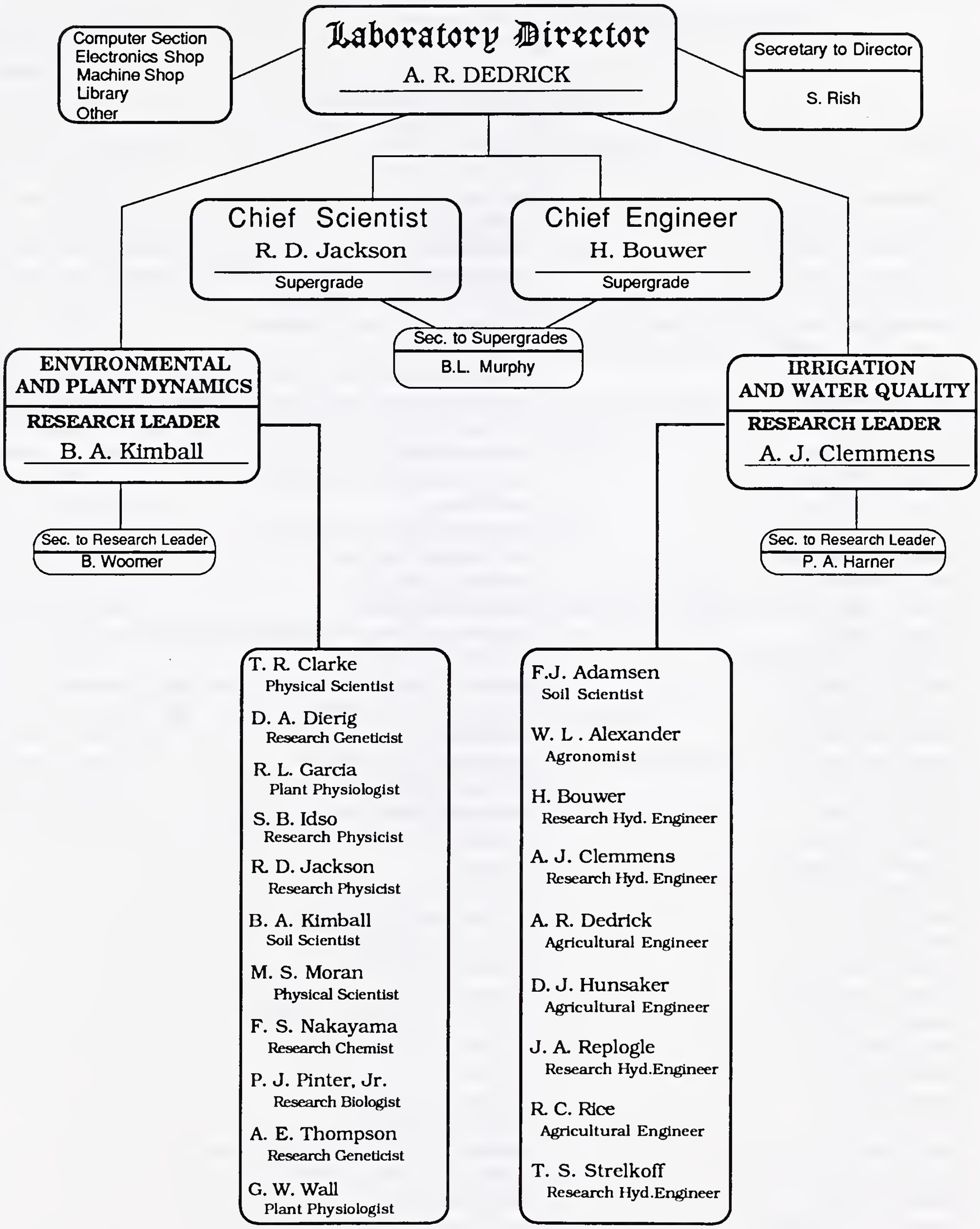
The mission of the Environmental and Plant Dynamics Research Unit is to develop optimum resource management strategies to meet national agricultural product requirements within the context of possible changes in the global environment. Specifically, the unit seeks to develop new methods to assess water and carbon dioxide fluxes in the soil-plant-atmosphere system, quantify plant stress and its effect on crop yield, and to predict effects of increasing carbon dioxide and climate change on plant growth and water use; develop suitable new and alternative crops to meet national needs for renewable, agriculturally-based industrial products; and develop remote sensing and related techniques as tools in water conservation, irrigation scheduling, drought prediction and avoidance, and to monitor crop conditions and assess environmental change. The program is designed to meet challenges and opportunities imposed by dynamic environments, particularly those stressful to plants, and their possible effects on crop production. A theme of increasing plant water use efficiency and conserving and improving the quality of agricultural water supplies unites these efforts. To these ends, the organization is closely knit and multidisciplinary, underlain by a philosophy of devising multifaceted approaches to critical problems associated with global environmental changes.

Increased funding for water quality and global change research strenghtened these programs. The increased funding allowed some scientific staff increases during 1991. In I & WQ, Dr. Floyd J. Adamsen, Soil Scientist; and Dr. Fedja S. Strelkoff, Research Hydraulic Engineer, joined the USWCL staff. Dr. Adamsen transferred from the Peanut Production, Diseases & Harvesting Research Unit at Suffolk, Virginia, and will work on water quality issues. Dr. Strelkoff, previously in private practice in San Francisco, will concentrate on hydraulic issues associated with surface irrigation and canal modeling. In E & PD, Dr. Gerard W. Wall, Plant Physiologist, and Dr. Richard L. Garcia, Plant Physiologist, joined the staff. Dr. Wall transferred from the Crop Circulation Research Unit, Mississippi State University, Mississippi State, Mississippi, and will concentrate on future development of $COTCO_2$, a cotton simulation model sensitive to CO_2 concentration. Dr. Garcia recently graduated from the University of Nebraska and joined the staff in a Post Doctorate position. He will work with the CO_2-climate change program concentrating on environmental influences on crop productivity.

The USWCL has aggressively and successfully pursued cooperative and collaborative arrangements with a number of organizations during 1991. Outside funding, in support of the research program at the USWCL, has come from Agrigenetics, Jojoba Growers & Processors, Department of Energy, Department of Defense, USDA-Soil Conservation Service, USDI-Bureau of Reclamation, Arizona Department of Water Resources, and the Binational Agricultural Research & Development Fund (BARD). Cooperative agreements with a number of other organizations are instrumental in positively impacting our research program. To these many cooperators, we say thanks.

We invite you to use this Annual Research Report. Let us know if there are questions or comments; all are invited and will be appreciated.

Allen R. Dedrick
Director



December 31, 1991

Table 1. U.S. Water Conservation Laboratory Staff

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Alexander, William L.	Agronomist
Anderson, Robert J.	Biological Technician (Resigned 1/11/91)
Arterberry, Carl A.	Agricultural Research Technician
Auer, Gladys C.	Physical Science Technician
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Research Leader and Supervisory Research Hydraulic Engineer
Craft, Michael R.	Physical Science Technician (Resigned 5/17/91)
Dedrick, Allen R.	Laboratory Director and Supervisory Agricultural Engineer
Dierig, David A.	Research Geneticist (Plants)
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary
Heckhart, Donna J.	Office Automation Assistant
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Jackson, Ray D.	Research Physicist
Johnson, Earl J.	Agricultural Research Technician (Plants)
Johnson, Stephanie M.	Biological Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
LaMorte, Robert L.	Engineering Technician
Lewis, Clarence L.	Machinist
Martinez, Juan M. R.	Hydrological Technician
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Programmer Analyst
Moran, M. Susan	Physical Scientist
Murphy, Benita L.	Secretary
Nakayama, Francis S.	Research Chemist
Padilla, John	Engineering Technician
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Rasnick, Barbara A.	Physicial Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rice, Robert C.	Agricultural Engineer
Rish, Shirley A.	Secretary
Rokey, Ric R.	Biological Technician
Seay, L. Susan	Publications Clerk
Seay, Ronald S.	Agricultural Research Technician
Thompson, Anson E.	Research Plant Geneticist
Wall, Gerard W.	Plant Physiologist
Woomer, E. Elizabeth	Secretary

TEMPORARY EMPLOYEES

Aberouette, Maritza	Physical Science Aide (Resigned 6/16/91)
Bhattacharya, N.	Plant Physiologist
Bertrand, Brian L.	Biological Aide
Corsnitz, Kim E.	Biological Aide
Freitag, Laurel A.	Laboratory Helper
Geldmacher, Tom R.	Biological Aide (Resigned 8/19/91)
Garcia, Richard L.	Plant Physiologist
Graham, Barry G.	Computer Clerk
Henry, Douglas J.	Biological Aide
Johnson, Michael S.	Physical Science Aide
Klosterman, Evelyn M.	Biological Aide
Lattanzio, Mario	Physical Science Aide (Resigned 9/26/91)
Moore, Allen L.	Work Study, AZ State University (Resigned 5/31/91)
Motl, James S.	Physical Science Aide (Resigned 12/12/91)
O'Brien, Carrie C.	Biological Aide
Padilla, Janet R.	Biological Aide (Resigned 6/7/91)
Perschbacher, Marcella	Biological Aide (Resigned 4/25/91)
Pizmont, Ronald M.	Physical Science Aide
Pizzi, Judith A.	Biological Aide
Reaves, Matthew L.	Physical Science Aide
Rebman, Jon P.	Biological Technician
Renfrow, Roger R.	Biological Aide
Rice, Kathleen C.	Biological Aide (Resigned 9/7/91)
Schmidgall, Scott L.	Physical Science Technician (Resigned 7/26/91)
Schwei, Matthew	Biological Aide (Resigned 9/7/91)
Smith, Sue N.	Biological Aide
Strand, Robert J.	Engineering Aide
Strelkoff, Theodor S.	Research Hydraulic Engineer
Villalobos, Miguel A.	Biological Aide
Wahlin, Brett R.	Biological Aide (Resigned 11/30/91)
Wahlin, Brian T.	Engineering Aide
Weber, Robin L.	Biological Aide

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INTEGRATED IRRIGATION SYSTEM WATER MANAGEMENT

MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR IRRIGATED AGRICULTURE

A.R. Dedrick, Supervisory Agricultural Engineer;
A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
J. A. Replogle, Research Hydraulic Engineer

PROBLEM: Improved water management is essential to a sustainable irrigated agriculture. Farmers, irrigation districts, and support organizations must interact in ways appropriate to long-term resource management, environmental protection, and social well-being. Across the irrigated West, the most immediate problem farmers face is increasingly scarce water supplies. Farmers, especially those in irrigated agriculture, will need to improve their approach to water management or face economic, legal, or societal induced failure.

The purposes of this work are to develop, apply, and evaluate the Management Improvement Program (MIP) methodology for improving resource management and organizational effectiveness. The MIP, a management process not unlike that commonly applied to improve the performance of business organizations, is being applied to the business of irrigated agriculture by looking specifically at overall profitability and sustainability within an irrigated area. Expected outcomes from this program include 1) improved communication and collaboration among farmers, districts, and government agencies, which will strengthen working relationships among agencies and improve their effectiveness; 2) better understanding of the current status of, and problems and opportunities in, water resources management, including irrigation district operations, on-farm water management, and similarities and differences between districts; 3) identification, selection, and implementation of alternative actions (research/educational programs) to improve irrigation operation and management of farm irrigation and water delivery systems; 4) increased farmer profit/benefit; and 5) increased understanding of MIP application as a tool in a range of situations.

APPROACH: In 1990, under the direction of the U. S. Water Conservation Laboratory, an interagency program was initiated to assess 1) the MIP's potential for improving irrigated agriculture for the benefit of farmers and agriculture-related organizations within an irrigated area; 2) the MIP's usefulness in identifying opportunities for technology transfer to growers and organizations and for organizational change for various agencies serving irrigated agriculture; and 3) the MIP as a strategic process for application to irrigation projects elsewhere. Agencies involved had an interest in the potential of the MIP to support improved irrigated agriculture productivity, profitability, and natural resource management. An MIP Coordinating Group (CG) was established to direct the MIP (Table 1). To properly assess the MIP process, a demonstration MIP, to be conducted with an irrigation district, was initiated in early 1990. In December 1990, the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) agreed to cooperate in the demonstration program (MSIDD MIP). A planning workshop for the MSIDD area Diagnostic Analysis (DA), the first phase of the MIP, was held April 22-26, 1991. Key milestones in the MSIDD MIP during 1991:

1) <u>DA planning</u> included selecting a DA Core Team, holding periodic core team meetings, and developing fieldwork guidance products. The DA Core Team (Table 2) was charged with carrying out the DA phase of a district-specific MIP. Consultants to the MIP, and serving as part of the DA Core Team, included a management/team-building specialist, with responsibility to frame and link each of the particular events and lead their overall facilitation; and an MIP specialist, who provided both technical and process guidance supporting each disciplinary effort, as well as the overall interdisciplinary team. A larger group, the DA Resource Team, selected because their knowledge and experience related either to the technical aspects of the particular irrigation system or to the DA process, assisted in preparing the DA Core Team and providing critical review of the evolving DA findings as well as the MIP process.
2) <u>Data collection</u> included obtaining information from both published background sources and personal interviews of MSIDD Board of Directors (BOD), management, staff, and employees; and growers, foremen, and irrigators. The DA Core Team summarized and synthesized these data during and immediately after the data collection process.

3) Data summary and synthesis included initial interpretation by the Core Team from their original findings, and subsequently with input from the Resource Team, MSIDD BOD, MSIDD Staff, and the CG.
4) Finalization of the DA included completing data collection and analysis, developing and reviewing a report of the DA, presentation of results, and linkage to the Management Planning (MP) phase of the MIP. The two-volume MSIDD DA Report is nearing completion. The Table of Contents for Volume I is shown as Table 3. Volume II provides backup data and analysis in support of the MSIDD DA.

FINDINGS: The findings include only performance issues that the Core Team saw as priority in terms of impact. Three areas of emphasis were used: overall economic viability of irrigated agriculture in the district; management of the farm units, MSIDD, and their interfaces; and technology upgrading and new technology adoption, both on- and off-farm. The report communicates the interdependence of system elements and the resulting coordination requirements for involved groups. Economic issues are critical to the survival of the MSIDD and the growers. Management issues are important to MSIDD, various supporting organizations, and the growers and their interface with each other. Technology issues are important to the growers for sustaining and improving performance under the changing water supply and economic conditions, to MSIDD for continued improved performance, and to relevant agencies for support and involvement in improving irrigated agriculture. The understanding of performance for each emphasis was documented in a structured format that included objectives for system achievement; performance statements describing actual system performance; impacts describing the effects of the performance; and contributing factors explaining the causes of the level of performance.

INTERPRETATION: The interdisciplinary approach used in the MIP process provides a rich and useful departure point from more traditional, single disciplinary approaches to problem solving and encompasses a real world understanding of performance. By fully understanding the causes of either high or low performance, appropriate plans of action can be identified. The MIP Coordinating Group, using the demonstration MIP as a guide, is confident that the MIP process can positively impact irrigated agriculture and during 1992 will consider broadening the scope of the present program. The DA findings, reviewed to date by the MSIDD Board of Directors, the MSIDD Staff, and the MIP Coordinating Group, reportedly have been "on target." The structure for presenting the DA findings has proven effective in achieving and communicating a synthesized interdisciplinary understanding of the performance of an irrigated agricultural system. The presentation approach integrates the input of management and field personnel both on-farm and in MSIDD and DA Team observations. The demonstration MIP has progressed satisfactorily, although not without expected challenges associated with the management of various teams, coordinating various interested parties' input to the MIP, obtaining needed funding, and dealing appropriately with the various sensitive issues encountered.

FUTURE PLANS: The demonstration MIP will be continued in the Maricopa-Stanfield Irrigation and Drainage District with Phase II, the Management Planning Phase, scheduled for completion during the first half of 1992. Phase III, the Management Performance Phase, in which the plans developed from Phase II are initiated and appropriate monitoring and evaluation programs are instituted, will follow. A Coordinating Group retreat is planned for late January 1992 to consider expansion of the organizations involved in the interagency MIP; to update upper management in the various cooperating agencies on the purpose, history, and current status of the Interagency MIP; and to further define what might be the appropriate mandate for the Coordinating Group over the next two years, including additional applications of the MIP methodology.

COOPERATORS: Maricopa-Stanfield Irrigation and Drainage District, U. S. Bureau of Reclamation, Soil Conservation Service, University of Arizona Cooperative Extension, Arizona Department of Water Resources, Arizona Department of Environmental Quality, and Colorado State University.

Table 1: Current Coordinating Group agencies and representatives.[1]

AGENCY	REPRESENTATIVE
Agricultural Research Service (USDA)	Allen R. Dedrick, MIP Project Leader
Bureau of Reclamation (USDI)	Stanley G. Conway, Chief, Irrigation Management Service Branch
Soil Conservation Service (USDA)	Robert B. Crawford, State Resource Conservationist
Arizona Department of Water Resources	Thomas G. Carr, Director of Pinal AMA
Arizona Department of Environmental Quality	James F. DuBois, Hydrologist
University of Arizona Cooperative Extension	Thomas F. Scherer[2], Irrigation Specialist

[1]Wayne Clyma, MIP Specialist, David B. Levine, Management/Team-Building Specialist, and Shirley Rish, Secretary, serve as consultants and staff to the Coordinating Group.

[2]Scherer was a member until he transferred to a new position in June 1991. The Cooperative Extension position on the Coordinating Group has not been filled.

Table 2: Maricopa-Stanfield Irrigation and Drainage District Diagnostic Analysis Core Team (MSIDD DA Core Team) members and support; subsystem, or role for which each was responsible; and affiliation.

NAME	SUBSYSTEM OR ROLE	AFFILIATION
Allen R. Dedrick	Project Leader	Director, USDA-ARS, U. S. Water Conservation Laboratory (USWCL), Phoenix, Arizona
Paul N. Wilson	Economics	Associate Professor, Department of Agricultural Economics, University of Arizona, Tucson, Arizona
Richard D. Gibson	Social-Organizational	Extension Agent-Agriculture, University of Arizona Cooperative Extension, Pinal County, Casa Grande, Arizona
Ralph E. Ware	Productivity	Soil Conservationist, USDA/Soil Conservation Service, Casa Grande Field Office, Casa Grande, Arizona
John A. Replogle	Water Control: Delivery	Research Hydraulic Engineer, USDA-ARS, USWCL, Phoenix, Arizona
Albert J. Clemmens	Water Control: On-Farm	Research Hydraulic Engineer, USDA-ARS, USWCL, Phoenix, Arizona
Wayne Clyma	MIP Specialist	Professor, Agricultural and Chemical Engineering Department, Colorado State University, Fort Collins, Colorado
David B. Levine	Overall Process Guidance	Private Consultant (Management, Strategic Planning and Team Building), Washington D. C.
Shirley A. Rish	Communications/ Organizational Resource	Secretary, USDA/ARS, USWCL, Phoenix, Arizona

Table 3: Table of Contents for the MSIDD DA Report (Volume I).

IRRIGATION FLOW MEASUREMENT STUDIES

J. A. Replogle, Research Hydraulic Engineer

PROBLEM: Water Flow measurement continues to be a major tool for improving management and conserving water in irrigated agriculture. Problems with flow rate devices include their relative complexity, required training level of field users, and economics of installation and operation. The objective of this project is to develop flow measurement technology and equipment which improves convenience of use and reduces training requirements.

APPROACH: We are re-visiting a selection of old techniques with a view to updating them in the light of more recent understandings of fluid dynamics and advances in secondary instrumentation. Even with the success of the long-throated flumes for measuring flow in canals, there are many canals for which the small head loss that they require for accurate measurement cannot be readily provided. We are evaluating such things as the statistical reliability of field constructions and their tolerances with regard to acceptable accuracy. Pipeline flows that take their water from canals have a unique set of problems that need addressing.

a) Venturi meters were constructed from light weight plastic irrigation pipe fittings for use as a low cost measuring device for low-head pipelines. The pipe is rated for 50 psi. The size chosen was 12-inch main line reduced to 8-inch pipe for a distance of 2 feet then expanded again to 12 inches. This provided an area contraction ratio of 0.444, which was chosen to provide reasonable pressure differentials of between about 0.5 feet and 3 feet. Construction control problems was evaluated by having 3 different people construct the devices although most of them were constructed by one technician. Over 15 constructions were made to provide statistical data for evaluating the reliability of non-factory construction. All but the final configuration was constructed symmetrically from end to end so that reversing the devices provided over 30 test configurations. The "final" construction included an attached upstream pressure tapping while the reversible versions used a common tapping in the supply pipe. Laboratory calibrations relied on a weigh tank for comparison flow rates. The weigh-tank method is reliable to better than $\pm$ 0.1%.

b) The wide spread installation of long-throated flumes and sonic meters in many canal sizes throughout Arizona and California offers an opportunity to evaluate the variability of float/velocity methods as a simple measuring technique on a grand scale not easily available to previous generations of researchers. In preliminary testing, multiple floats made of colored ice cubes and dyed popcorn were simultaneously dumped above a starting point in a small farm canal and timed over 100 feet of travel distance. The lead particle was timed in the field. Video of the various drops allowed the subsequent retiming of other than the lead particle. For example the popcorn was more sensitive to wind direction than the ice cubes, however, the melting ice cubes tended to stick to the dump-tray until after the popcorn had hit the water. Subsequently the popcorn got a head start and dominated the timing runs. Subsequent timings on the ice cubes have not yet been taken from the video tapes. A special ditch caliper was built. It can readily and accurately measure the top width and flow depth of canals up to about 12 feet wide and about 6 feet deep. This was needed to reduce the error in determining the flow area .

c) A new style of force meter for open channel flow measurement is being developed. Basically the mechanism is a triangular blade suspended in a rectangular section of channel using a frame. The force on the blade is transferred to a load cell. This force is related to the water flow rate. Other mechanical innovations allow it to be portable, non-sensitive to whether it is precisely vertical, and able to indicate flow rate per unit of width without specific knowledge of flow depth. The triangular blade is specific to rectangular channels. The device is scheduled for testing in the laboratory glass-sided channel and field canals. Shapes have been calculated for various trapezoidal channels, but they are not easily constructed without a computer-driven milling machine. Also to be evaluated is the response of the blade to the distribution of velocities in the channel profile. It is anticipated that this can be handled as indicated by theory.

FINDINGS: a) An adjustable flume reported on last year has been submitted for the patent process. The present patent was filed with the U.S. Patent Office in October. Its status is not known.
The basic construction for the expected final version of the plastic pipe Venturi is shown in Figure 1. The usually available parts required us to reduce from the 12-inch pipe to the 8-inch pipe in two stages as indicated. A clear plastic tube manometer with provision to "vacuum" the readings to a height for convenient reading is also shown. The overall length is greater than the standard-type Venturi tube, as indicated in the smaller diagram. The calibration coefficient, shown in Figure 2, is similar to that for a standard Venturi, but is about 3% lower at all points on the curve. The solid line of Figure 2 connects points as measured on the "final" construction configuration. Note that one end of the curve appears to be about 0.5% higher than the mass curve average (dashed line) and the other end is about 0.5% lower. The head loss for the plastic Venturis was about 8 inches for a maximum test flow rate of about 5.8 cfs. This was about 18% of differential head using pipe fittings with the more gentle 3:1 convergences, and 25% for sharper convergences of 2:1 (Figure 3). Standard-type Venturi tubes range from about 10% to 14% for 4:1 to 12:1 convergences. While the head losses for the two plastic venturi convergences were significantly different from each other, the calibrations were the same.

b) The multiple float method was applied to only one well-maintained farm canal flowing at 7.2 cfs as measured with a sonic meter used by the irrigation district. The velocity of the maximum surface filament was measured to be 2.56 ft/sec with a standard deviation of ±1.5% based on 16 replications in the same canal at a steady flow rate. The ratio of the canal average velocity to this maximum surface velocity was 0.76. The expected value from preliminary theoretical considerations had indicated it might be about 0.83 to 0.85.

c) No laboratory data have been collected on the force-velocity, or target meter device.

INTERPRETATION: a) Venturi meters can be satisfactorily constructed from commercial plastic irrigation pipe fittings. The head losses are nearly twice as large as an optimum Venturi meter, but should not be more than 6-inches for a maximum flow rate of 4.5 cfs. The useable pressure-differential range of about 1 inch to 28 inches, should be readable with sufficient precision by field usable methods. This Venturi construction should resist clogging, be easily constructed from parts costing about $100, and should be durable.

b) The generally small standard deviation on determining the maximum surface velocity in lined irrigation canals using multiple floats is encouraging in that it may correlate reliably to the average velocity as hoped. The deviation from the expected velocity ratio, however, needs to be explained.

c) Earlier work with shaped vanes by others has established their reliability when not allowed to deflect with the flow. That is, the blades are restored to position and the restoration force is measured. The hope is that the portable device can be developed as a convenient flow rate survey tool. Previous methods are time consuming and require the manipulation and plotting of much data.

FUTURE PLANS: a) A venturi meter construction and readout manometer will be demonstrated for the Soil Conservation service to copy for a field installation near Springerville, AZ. The basic laboratory data that establishes the discharge coefficient and the pressure losses will be presented in a paper at a July conference.

b) Plans are to move the project on float velocity methods to the field next spring when numerous canals with flumes of known reliability are available. Some flumes has the potential to furnish two data sets on each flow, one upstream of the flume and one downstream. Many flow rates and canal sizes are needed to explain or to establish the velocity ratios as possible functions of area aspect ratio, canal roughness, and relative velocity.

c) The force meter will be laboratory evaluated for its expected functions. Attempts to extend it to serve as a weir-overfall measuring device will be investigated. There is preliminary evidence that it might be able to function as an advanced "weir rule."

COOPERATORS: Soil Conservation Service

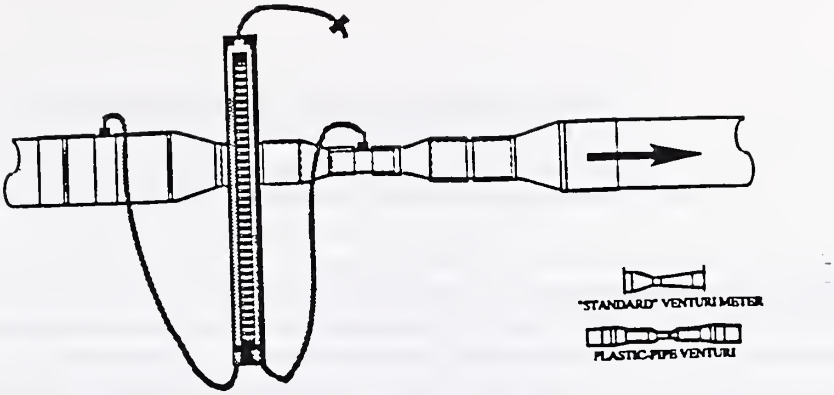

Figure 1. Layout for Plastic Pipe Venturi Meters

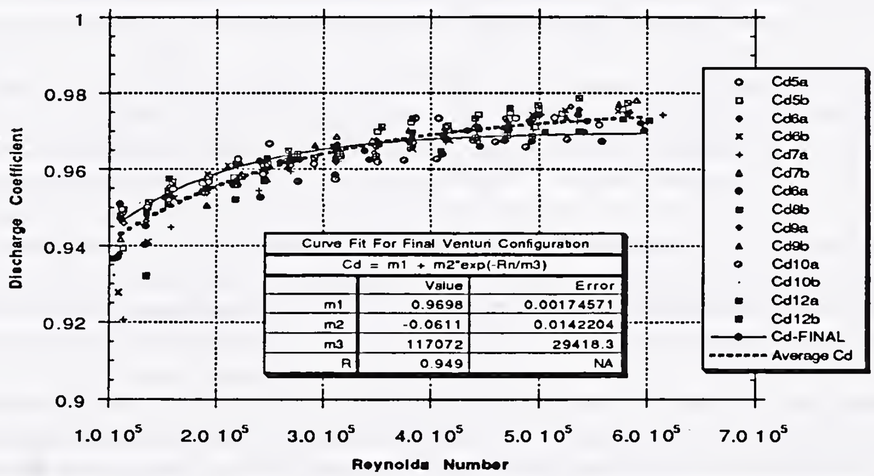

Figure 2. Calibration Coefficient for Plastic-Pipe Venturi Meters

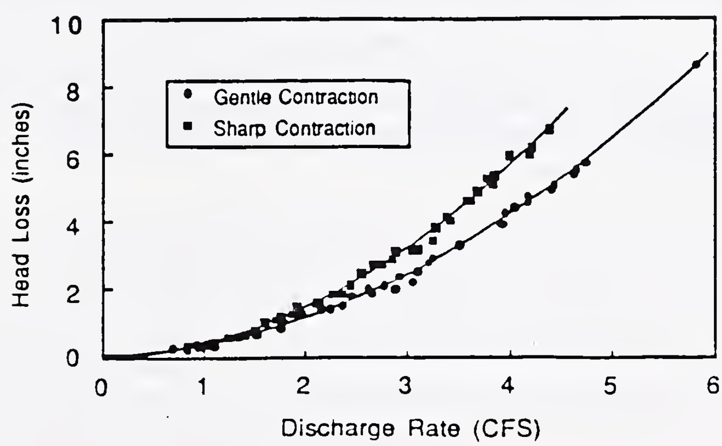

Figure 3. Head Loss Through 12-Inch, Plastic-Pipe Venturi Meters

SOFTWARE FOR DESIGN AND CALIBRATION OF LONG-THROATED MEASURING FLUMES

A.J. Clemmens, Supervisory Research Hydraulic Engineer and
J.A. Replogle, Research Hydraulic Engineer

PROBLEM: Flow measurement in irrigated agriculture continues to be a difficult problem. Flow measurements are frequently inaccurate, and structures are often improperly installed. Over the last decade, the long-throated flume has been developed as a very useful tool for improving water measurement in irrigation canals. One of the advantages of this device is that it can be custom designed for each installation, thus better meeting the needs of the measurement site. This can be a disadvantage in that it gives the user so much flexibility that an optimum structure may not be selected.

A computer program, FLUME, has been available since 1987 for the calibration of these flumes. It is not very user friendly; users frequently make errors in data input; and laboratory personnel spend a significant amount of time answering user questions. Thus, there is a need for a more user friendly flume program which can aid the user in design of these flumes.

APPROACH: A menu-driven program, FLUME3.0, is being developed to aid in the design and calibration of long-throated flumes for irrigation canals and natural channels. The program will include design procedures developed over the last few years. The user will input the conditions of the canal and select the type of contraction desired. Then the program will come up with a structure that meets the channel conditions. The program also has graphic data input which shows the flume profile and cross sections so that when the user enters flume dimensions, the changes can be viewed immediately. This should greatly reduce the chance of user error. The project is being sponsored by the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. A software programmer from Wageningen is under contract to ILRI to write the menu-driven program.

FINDINGS: The main parts of the program have been written, and a near final version of the program has been completed. The design routines were reprogrammed, tested, and debugged. The program has been demonstrated to users and is currently under review. Most of the program manual has been revised according to reviewer comments and changes to the program. The program should be available for distribution by mid-1992.

INTERPRETATIONS: This program should help the transfer of this technology to users in a very effective manner. It will make these flumes an even more valuable tool for improving water management in irrigated agriculture.

FUTURE PLANS: Completion and maintenance on the computer program FLUME3.0.

COOPERATORS: M.G. Bos, International Institute for Land Reclamation and Improvement, and J.M. Groenestein, Groenestein and Borst, Ltd.

IRRIGATION CANAL HYDRAULICS

T.S. Strelkoff, Research Hydraulic Engineer and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Surface-irrigation efficiency can most easily achieve high levels when the supply canals have been designed, and are operated, in a way to supply the necessary water at the right time to each of the users of the resource. In present systems, the possibility of meeting the canal-delivery requirements for efficient demand irrigation is not assured. The operation of gates and pumps in a canal system produces waves, which transmit the effects of these operations throughout the system at a speed not much in excess of water velocity. The total effect at any location is the combined result of these waves, transformed during their travel, that arrive there from their points of origin. Numerical simulation of the unsteady flow encountered in irrigation canals allows predicting the results of given physical designs and management procedures.

Many computer models of unsteady canal flow have been built in the last twenty years, some very complex and expensive, designed to model very complicated systems. Proprietary code is not readily accessed for modification to reflect new operating conditions or for incorporation into optimization routines. Some models, adopted by agencies and associated with years of experience, are reliable except when, physically, a hydraulic bore forms. Only rough, rule-of-thumb means are presently available for judging bore formation, and use of an unsuitable model for simulation of these cases leads to incorrect results, not necessarily identifiable.

APPROACH: A simple model containing essential features of a controlled canal can be used to answer generic questions regarding mathematical simulation of unsteady open-channel flow and also hypothetical questions about canal flow in general. The issue of bore formation can be studied most reliably with a model based on the method of characteristics, and furthermore, in a technique that allows at least one family of characteristics to remain continuous. This technique is not the most efficient one for general use, so a suitable model allows substitution of one approach for another. The current plan is to provide one subroutine based on the method of characteristics with construction of the full characteristic grid and another based on mass and momentum conservation applied to a grid based on lines of constant time and space.

FINDINGS: The generic model is currently under construction. Of several characteristics-based approaches programmed, several proved to exhibit excessive volume errors. The current version uses the characteristics grid for solution nodes and avoids all interpolation in solution construction. Second-order numerical integration of the equations along the characteristic curves leads to iterative, simultaneous solution of nonlinear algebraic equations by the Newton-Raphson method.

INTERPRETATION: Something is lost in every approach to simulation of unsteady open channel flows. Comparing the results of different techniques provides a perspective for viewing the results of any one model.

FUTURE PLANS: The characteristics-based model, when debugged and operational, will be run under a variety of initial conditions and rates of change of discharge at a boundary. Those conditions which lead to the spontaneous formation of a bore, even deep in the interior of the flow well away from the source of the change, will be identified. Nondimensional combinations of the pertinent variables will be used to simplify the presentation of the results.

The model will be available in-house to answer questions about simulation or canal behavior as these arise. Dissemination of the information gleaned will be encouraged by the participation of the researchers in an ASCE Task Committee on Irrigation Canal Modeling.

COOPERATORS: None

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly, and locally, in excessive amounts, leading to wastage and to pollution of ground and surface waters receiving the excess. The interaction of the many variables significantly influencing the movement of irrigation streams down fields, and, ultimately, the distribution of infiltrated water and the amount of runoff from the irrigation, is too complicated for simple calculation. A mathematical model--a numerical, computer solution of the pertinent governing equations--supplied with the conditions of the irrigation can, on the other hand, allow rapid determination of the consequences of a given physical design and management procedure. Systematic, repeated simulations allows determination of design parameters to yield optimum uniformity of infiltrated water and minimum runoff from the end of the field, as reported under a separate research project. This, in turn, can reduce the degradation of ground water supplies by excess irrigation water, contaminated by fertilizers and pesticides, percolating below the root zone of the crop. Similarly, reduction and re-use of field runoff protects surface-water supplies downstream from irrigated fields. Current models of surface irrigation require further development to extend the range of conditions they are designed to simulate, and to increase the reliability of their mathematical procedures. New irrigation techniques generally precede attempts at simulation, so models must be revised to allow theoretical testing of the innovations. Furthermore, present models do not always complete a simulation. A physical condition that can arise with severely cut-back flows is a temporary recession of the leading front of the stream, eventually halted, then once again moving forward. The present model can not simulate this motion. In addition, certain flow conditions, notably, very slow advance, on the order of a foot per minute, with potential, incipient front-end recession, present poorly posed problems, both physically and mathematically. A potential computer response is the generation of a negative depth, which stops the calculation if inflow, however small, at the head end of the field has not yet been cut off. Both physical circumstances are likely to occur in the investigation of practices leading to efficient irrigation; the inability to simulate these hampers the search for an optimum design.

The current ARS surface-irrigation model, furthermore, utilizes proprietary (shareware) drivers for graphical display of results, reducing the application of graphics in the model and the convenience of distribution of the software to interested parties.

APPROACH: Additional programming and some reprogramming is required to extend the scope of application of the model. The equations governing the flow of water in the surface stream are known, and computer algorithms for solving these are generally straightforward. An exception is the case of non-monotonic stream advance, as a reasonable assumption regarding the effect of rewetting upon infiltration will have to be devised. The current approach to very slow advance is to consider it to occur in a series of stair steps, periodically halting, building up behind a hypothetical barrier, and restarting, the process averaging out to the actual, slow, continuous advance.

FINDINGS: The current version of the surface-irrigation simulation program, SRFR -- Version 20, has been distributed in the present year to dozens of interested parties, in the U.S. and abroad, including several SCS offices. The current three surges of uniform flow pattern is inadequate to simulate current practice in surge-flow irrigation. At least six or seven surges, with a variable duration time are required. A preliminary, updated version of SRFR with seven variable surges, and with overtopping of furrows at the downstream end allowed, has been released to the South Central Research and Extension Center of the University of Nebraska.

Furthermore, the physical downstream boundary condition postulated in the current version as the alternative to water ponded behind an end block, free overfall into a drainage ditch, is not realistic in the light of standard irrigation practice. An alternative, postulated in some models, normal depth, also is not physically realistic, nor in fact mathematically compatible with any treatment of the flow more general than kinematic-wave analysis. Standard field practice, to prevent erosion, is to manage the water in the drainage ditch to flow at a level sufficiently above furrow bottom so that critical conditions are never achieved at field end.

INTERPRETATION: To make a significant impact on surface-irrigation design and practice, computer models of the process must be of broad scope, fast, and reliable, yielding simulations for every reasonable combination of circumstances, and with convenient graphical display of the results of any given set of design and management parameters. This is the aim of current development.

FUTURE PLANS: Current deficiencies in model behavior as outlined above will be addressed. Given the large size of the model and the memory limitations of most computers in the field, flexibility in distributing that memory to the greatest benefit of the user will also be addressed. The latest versions of compilers will be investigated for generating non-proprietary, custom graphics drivers compatible with the simulation code.

COOPERATORS: Dr. D.D. Fangmeier, University or Arizona; Dr. Joel Cahoon, University of Nebraska

SURFACE IRRIGATION SYSTEM DESIGN AND EVALUATION

A.J. Clemmens, Supervisory Research Hydraulic Engineer;
T.S. Strelkoff, Research Hydraulic Engineer; and
A.R. Dedrick, Laboratory Director

PROBLEM: The application efficiencies for surface irrigation systems continue to be poor despite advances in irrigation modeling and science. There are many reasons for this. In some cases, the irrigator or farmer has not chosen the correct flow rate or does not have sufficient control over water flow rate. In other cases, an inappropriate application time is used or a combination of inappropriate flow rate and application time are used. Proper design can sometimes greatly improve attainable efficiencies. In other cases, proper scheduling and knowledge of the correct amount to apply is sufficient. However, because infiltration and roughness can change dramatically over the season, it may be difficult for irrigators to correctly adjust flow rate and time to account for the conditions during the irrigation.

Mathematical models of water flow in surface irrigation have been developed over the last two decades. These are predictive models; that is, you supply the actual conditions (e.g., parameters describing infiltration, roughness, flow rate, length, etc.), and the model determines the results of the irrigation. However in many cases, the infiltration and roughness parameters are not known. While a number of parameter-evaluation techniques are available, different techniques are appropriate under different conditions. Even when conditions for one irrigation are determined, they may be quite different for other irrigations under different crops and tillage conditions. Design should consider performance over the full range of expected conditions. If the design is functional over the full range of conditions, adjustments needed by the irrigator should likely be minor from irrigation to irrigation. Feedback control (automatic adjustments based on real time evaluation of parameters) has been studied under a separate research project (see 1990 USWCL Annual Report).

The objective of this project is to develop user friendly software for the evaluation and design of surface irrigation systems that is usable in differing irrigation settings.

APPROACH: Reliable predictive models are the first step in the development of surface irrigation software. Model development is discussed under a separate research project. There are two approaches to developing design results; 1) to look up results already generated from a simulation model, and 2) to search for an acceptable (or optimal) design solution by successive approximation with the simulation model. With state-of-the-art computers, the former is still preferred, however as increasingly faster machines become available the latter provides more latitude in design objectives and field conditions.

Generalized design and management guidelines have yet to be developed from the models. These guidelines can be in the form of tabulated results, regression equations, or procedures for systematically applying the predictive models. This step is necessary for practical application of these predictive models. Several approaches will be taken in the development of these design guidelines. They include the development of; 1) nondimensional solutions for general problems (e.g., optimal design) that can be computer coded, 2) search procedures for more specific problems, 3) design procedures that take into account the changes in field parameters that occur over the season, and 4) sensitivity analysis of design input.

In addition, one must be able to include other factors which affect uniformity and efficiency, namely, soil spatial variability, surface irregularities, non-uniform inflow streams, etc. Various studies will be conducted to assess the impact of these conditions. Procedures will then be developed to account for these in the design and operating procedures.

One of the key limitations of existing programs, as discussed earlier, is that the user must be able to quantify field conditions for infiltration and roughness. There is a need for a general program on field evaluation procedures to assist users in determining field conditions for input into these design and operation programs.

Search procedures also need to be developed for finding optimal designs (e.g., determining length, slope, flow rate, etc.) which are efficient and robust. Most search procedures are not totally reliable when applied to surface irrigation modeling.

FINDINGS: The nondimensional design results for level basins were coded into a menu-driven design program. This program, BASIN, is intended to replace the SCS design charts for level basins. The program was distributed to several users for comment during 1991. The menu system was significantly revised in 1991, and a first draft of the users manual is nearly complete. BASIN should be available for distribution in 1992.

Grower surveys (discussed in more detail under the section on A Management Improvement Program for Irrigated Agriculture) on water use, field designs, soils and management practices were used to determine the most important factors affecting total seasonal water application. Field length of run and soil type were shown to be highly significant factors in water application, which somewhat reflects seasonal application efficiency. No relation was found between seasonal water application and yield (Figure 1). Growers who checked the adequacy of irrigation after each irrigation event used less water, which has implications for irrigation evaluation methods.

INTERPRETATION: While significant advancements have been made on the development of predictive models, significant impact will likely occur only when these models can be incorporated into some form of user friendly software. Only in this way will these models impact water use efficiency in irrigated agriculture. This must be done in the context of grower management practices. Significant insight was gained from the grower survey work complete as part of the Management Improvement Program.

FUTURE PLANS: A proposal has been developed with the International Institute for Land Reclamation and Improvement (ILRI) to: 1) expand the BASIN program to include field evaluation procedures, 2) include design based on cutoff at completion of advance (or some portion of advance distance), and 3) include statistical procedures to account for spatial variability and surface leveling precision. A book on level basins would be written to accompany the new program, BASIN2. This effort will take several years to complete.

Long range plans are to develop a general software package for surface irrigation systems along the lines of BASIN2, but expanded to include sloping borders and furrows and to include the actual simulation model as well as generated design results and evaluations.

The University of Michigan has developed search procedures for surface irrigation parameter estimation. We will examine these procedures to determine their suitability for use in design.

COOPERATORS: N.D. Katopodes, University of Michigan; D.D. Fangmeier, University of Arizona; T.A. McMahon, University of Melbourne; M. Jurriens, International Institute for Land Reclamation and Improvement; W. Clyma, Colorado State University

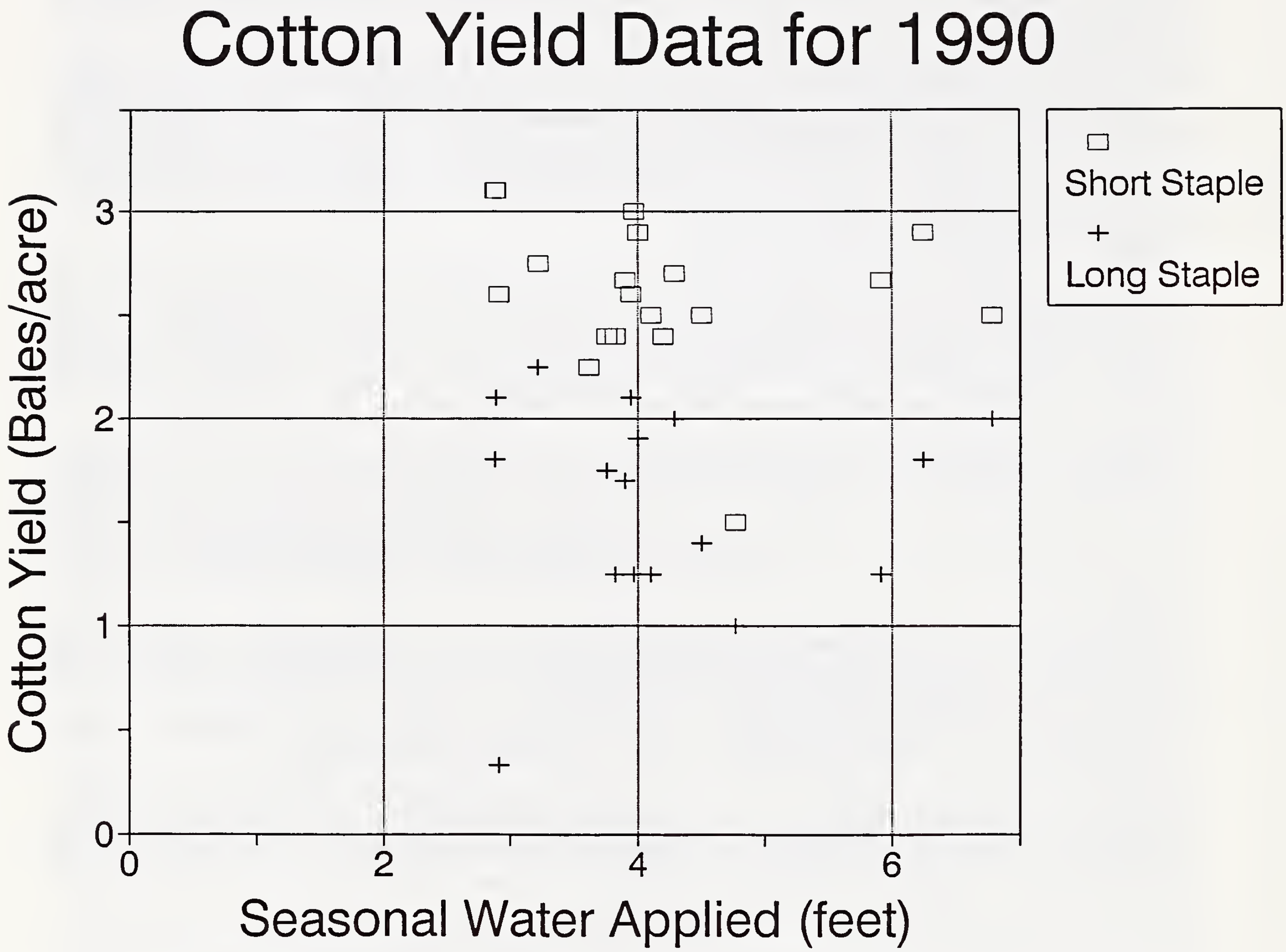

Figure 1. Cotton yield versus seasonal water applied for land supplied from sampled turnouts during 1990, MSIDD DA, Maricopa, AZ.

ACCOUNTING FOR SOIL AND IRRIGATION VARIABILITY IN CROP MANAGEMENT

D.J. Hunsaker, Agricultural Engineer

PROBLEM: Accounting for soil and irrigation system variability is required for optimum crop management. However, knowledge and description of this variability on crop yields and water use efficiencies are presently inadequate to establish appropriate water management practices.

The objectives are to (1) study and describe the effects of soil and irrigation system variability on crop water management and production under farm-scale, surface irrigation conditions, and (2) to develop irrigation management practices that minimize the effects of spatial variability.

APPROACH: A series of experimental studies have been conducted from 1985 through 1990 on a 4.2-ha, laser-leveled, sandy loam field site located at the Maricopa Agricultural Center in central Arizona. The field was separated into 12, 0.35-ha (14 by 251 m) basins. Experimental treatments have consisted of seasonal irrigation water quantity, irrigation water quality and basin length. Primary data collected included water delivery inflow rate and volume of water applied during each irrigation, irrigation advance, soil infiltration rates, soil water contents, soil texture, soil salinity, soil surface elevation and crop yield. Studies with wheat (previously reported) grown under level basin irrigation examined the effects of soil texture and volumetric soil water content variability on crop evapotranspiration (ET) and grain yield.

The effects of irrigation uniformity on cotton (cv Deltapine-90) grown in level basins were studied during the 1987 and 1988 crop years. In 1987, the basins were irrigated with high water inflow rates (110-180 l s^{-1}) to attain rapid water advance and minimize infiltration opportunity times. In 1988, water inflow rates were reduced by approximately 60% (60-110 l s^{-1}), to exacerbate irrigation nonuniformity, while applying the same average depth of water (100 mm per irrigation) as in 1987. Three irrigation treatments, High, Medium and Low received nine, seven and five seasonal irrigations, respectively, after 160 mm of water was applied for plant establishment in each year. Thirty-one yields were sampled in small areas (2 by 6 m) down the center rows of each basin so that the variability in yields could be measured and related to the variability in soil water as determined by neutron moisture measurements.

FINDINGS: Analysis of the 1987 and 1988 cotton experiments were completed. SRFR, a surface irrigation simulation model, was used to infer how the infiltrated water uniformity along a furrow was affected by the different inflow rates. A uniform field average infiltration characteristic was used so the magnitude of the DU_L reflects the irrigation system hydraulics. The calculated Low-Quarter Distribution Uniformity (DU_L) generated by the model varied from 86 to 92% for the higher flow rates used in 1987 and from 65 to 86% in 1988. The depth of water replaced in the 2.1-m soil depth (W) was determined at 16 neutron access tube locations down the furrow length of each basin for all seasonal irrigations. The seasonal average coefficient of variation (CV) of W was between 0.12 to 0.17 in 1987 and between 0.15 to 0.29 in 1988. Figure 1 shows the seasonal total depth of water for each location in the basin, averaged by irrigation treatment. The plots of Figure 1 illustrate that the distributions of the seasonal W were less uniform in 1988 than in 1987. In 1988, all three irrigation treatment distributions were characterized by large values of W near the basin inlet and a marked decrease in W over the last quarter of the field.

The results for the total water applied, seasonal ET, and lint yield for each irrigation treatment are summarized in Table 1 (1987) and Table 2 (1988). Over all irrigation treatments, seasonal ET decreased from 4 to 8%, and yield decreased from 11 to 21% in 1988 from 1987 totals. At the same time the CVs for ET and yield increased in 1988 over those of 1987. However, cotton yields at the Maricopa Agricultural Center farm were also lower in 1988 than in 1987. Short staple cotton lint yields from 221 hectares averaged 1978 kg ha^{-1} at the Center in 1987 compared to an average of 1743 kg ha^{-1} from 268 hectares planted in 1988. Relative lint yields (measured yield/average farm yields) are shown as a function of total applied water in Figure 2. In 1987, lint yields for the High irrigation treatment were about the same as the farm average but were about 8% lower than the farm average for the High irrigation treatment in 1988. Relative yields for the Medium irrigation treatment were about the same in both years (0.77-0.78),

while relative yields for the Low irrigation treatment were higher in 1987 (0.55) than in 1988 (0.50). Water use efficiency (total seed cotton per unit of applied water) is illustrated in Figure 3. In 1987, water use efficiency increased at the highest level of irrigation. In 1988, there was no difference in water use efficiency between the Medium and High irrigation treatments.

INTERPRETATION: Properly designed, level basin systems can apply water sufficiently uniformly that the highest yield and water use efficiency should be attained when irrigation scheduling matches the maximum seasonal ET. With less than optimum irrigation uniformity, increased yield variability can be expected to reduce average yields below potential levels even under 100% maximum ET scheduling. In these experiments when full irrigation was attempted in 1988 under the lower water delivery inflow rates, water use efficiencies were reduced by about 20% compared to those the previous year. In that situation, a grower may be better off eliminating one or two irrigations and applying a higher volume of water during other irrigations to attain better uniformity of water throughout the field.

FUTURE PLANS: The 1987 and 1988 cotton studies are being prepared for publication. Future research will emphasize accounting for spatial variability and preferential flow in Best Management Practices for water and fertilizer applications.

COOPERATORS: None

Table 1. Water Applied, estimated ET and lint yield, 1987 (coefficients of variation in parenthesis).

Irrigation Treatment	Total water applied [a] (mm)	Seasonal ET [b] (mm)	Lint Yield [c] (kg ha^{-1})
High	1118	961(0.08)	2014(.08)
Medium	918	845(0.08)	1523(.10)
Low	718	650(0.10)	1094(.18)

[a] Includes 160mm of water from preplant irrigation, plus effective rainfall totaling 58mm throughout the growing season.
[b] Seasonal ET (soil water depletion plus effective rainfall).
[c] Lint percentage averaged 33.4%.

Table 2. Water applied, estimated ET lint yield, 1988 (coefficients of variation in parenthesis).

Irrigation Treatment	Total water applied [a] (mm)	Seasonal ET [b] (mm)	Lint Yield [c] (kg ha^{-1})
High	1139	920(0.10)	1605(.11)
Medium	939	782(0.11)	1360(.14)
Low	739	621(0.14)	868(.25)

[a] Includes 160mm of water from preplant irrigation, plus effective rainfall totaling 79mm throughout the growing season.
[b] Seasonal ET (soil water depletion plus effective rainfall).
[c] Lint percentage averaged 35.3%.

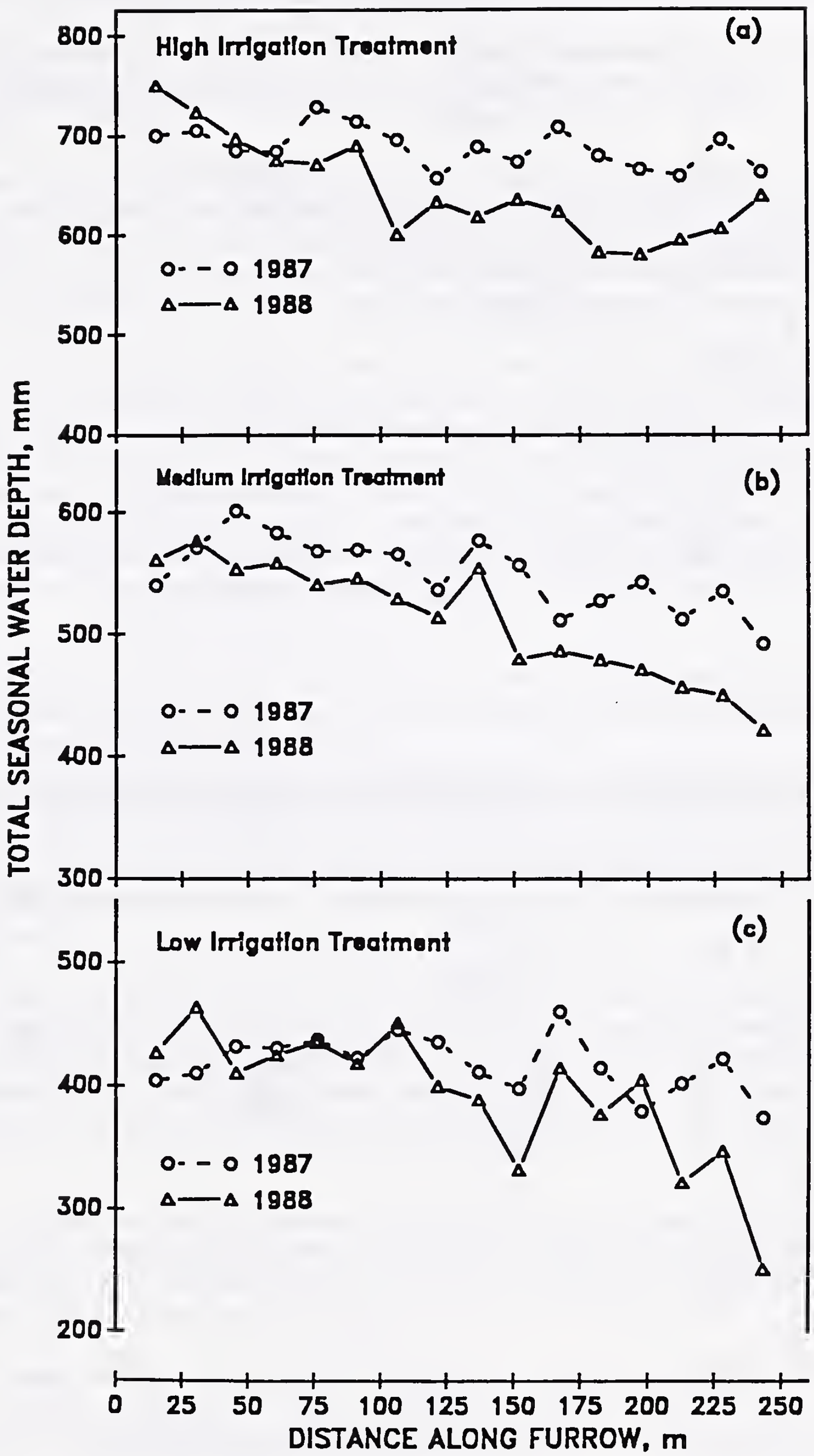

Figure 1. Distribution of total seasonal water depth for High, Medium and Low irrigation treatments in 1987 and 1988.

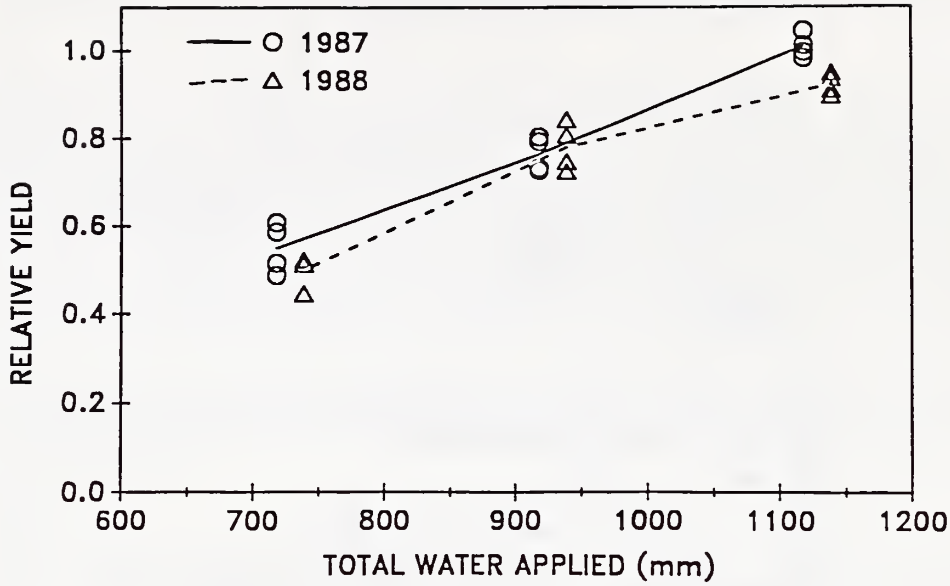

Figure 2. Relative lint yield (measured yield/average farm yield) as a function of total water applied.

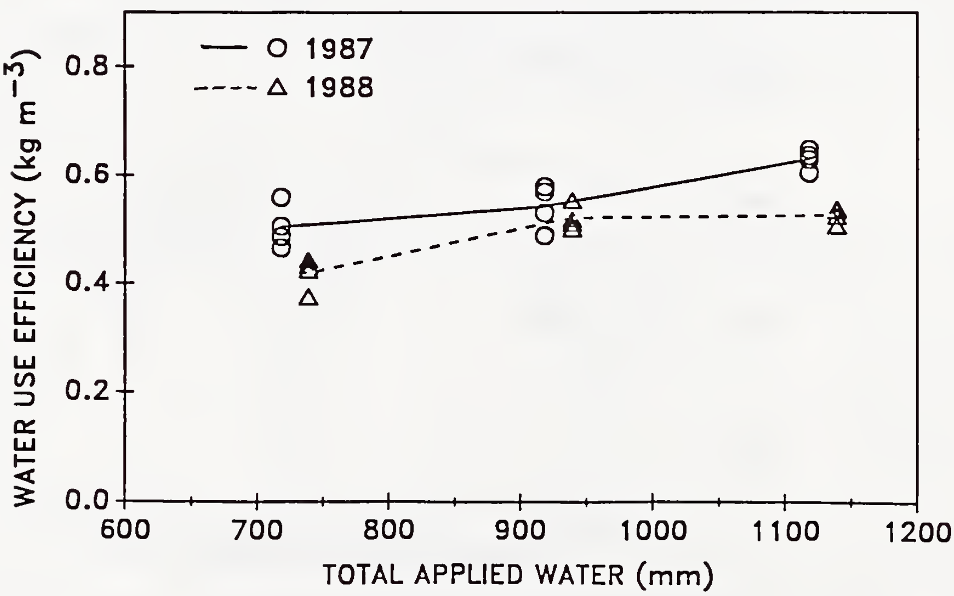

Figure 3. Water use efficiency (seed cotton yield per unit of applied water) as a function of total water applied.

EFFECTS OF PHYSICAL WATER TREATMENT ON TRICKLE IRRIGATION

D.E. Powers, Physical Science Technician; J.A. Replogle, Research Hydraulic Engineer;
F.S. Nakayama, Research Chemist; and W.L. Alexander, Agronomist

PROBLEM: Recent publications reported that the physical treatment of water used in trickle irrigation could increase crop yields. Specific reference is also made concerning the positive effects of magnetic and catalytic water conditioner units on soil chemical and physical properties. This research was set up to determine the validity of such reports to ensure that reliable results are being obtained and to study the effects, if any, of the treatments on the electrochemical properties of the trickle system.

APPROACH: A standard trickle irrigation system was set up for the cultivation of cantaloupe. Commercially available water treatment devices that included two types of magnetic conditioner and one type of catalytic unit were installed in the system following manufacturers' recommendations. Voltage measurements across the treatment devices were made and monitored during the irrigation runs. Emitter flow rates were measured throughout the study. Crop yield, sugar, petiole nitrate and leaf chlorophyll contents were determined. Irrigation water was analyzed for total salt, nitrate, pH, calcium and bicarbonate; soil solution extracts were analyzed for nitrate, pH, and total salt content. A completely randomized block design with six replications was used for the three different water treatment units and check.

FINDINGS: No significant difference were obtained in the emitter flow rates among the treatments, although there was a tendency for the treated water to have higher flow rates than the check. Cantaloupe yields were not significantly different (Table 1).

The other plant measurements were also not significantly different among the treatments. This was also the case for the soil solute and chemical water constituents. The soil solute compositions were extremely variable for this site and, therefore, were not useful for the statistical analyses.

The only notable behavior observed was the change in system voltage for all treatments over the period when the irrigation water was being passed through the trickle system. Explanation as to why this occurs is not available at present.

INTERPRETATIONS: No significant cantaloupe yield difference was found among several physical water treatment devices used to treat the trickle irrigation water. Our results contradict the report of Lin and Yotvat (1991). The equipment used by them was not available to us so there remains a question of whether such a device in our test system could have positively affected yield. Whether cultural practices could have been a factor is doubtful since the agronomic practices used in our experiments were standard for this area.

PLANS: Continue field and laboratory operation of the trickle irrigation system on a limited basis and concentrate on the unique voltage patterns observed in the preliminary measurements. Work with other types of electromagnetic water treatment devices that have other unique features including higher magnetic field strength than the one used previously.

COOPERATORS: Jack Watson, University of Arizona, Maricopa Agricultural Center.

REFERENCES: Lin, I.J. and Yotvat, J. 1991. Magnetic treatment of water contributes to agriculture. Irrig. J. 41(1):38-45.

Table 1. Cantaloupe Yield for Different Water Treatments

Treatment	Yield* (marketable/9 m^2)
Check	47 ns
In-line magnet	47 ns
Strap-on magnet	48 ns
Catalytic	45 ns

*Total number of cantaloupes for 12 harvests.

EFFECTS OF PHYSICAL WATER TREATMENT ON GREENHOUSE COOLING WATER

D.E. Powers, Physical Science Technician; F.S. Nakayama, Research Chemist; and J.A. Replogle, Research Hydraulic Engineer

PROBLEM: Salt and scale deposits on greenhouse evaporative cooler pads decrease the efficiency of the cooling system. They decrease cooling capacity and increase maintenance and replacement costs. Downtime for pad replacement cuts down on the use of the facility. Water treatment devices based on magnetic principles have been used to prevent scaling and corrosion in circulation systems. Preliminary studies were conducted to investigate the feasibility of using such devices to treat water used in cooling greenhouses.

APPROACH: Commercially available magnetic water treatment devices were attached to the cooler pad recirculating system in duplicate greenhouses. The water circulating system was in operation for one year prior to the installation of the devices. Treatment was conducted during the summer when the cooling system was in peak operation. Salt concentration in the water was determined by conductometric measurements. The water storage sumps were drained at least four times during the trial runs.

FINDINGS: In the first year (1990), between early July and late November, a significant lower soluble salt concentration was present in the magnetically treated compared to the untreated water (Figure 1). Similar results were observed for the succeeding 1991 year experiment that was conducted between early May and mid-November (Figure 2). The differences were less in the 1991 than 1990 experiment. The extent of scale deposit was not determined, but visual observations indicated a difference in the type of deposits for the different treatments. Large amounts of air-borne materials that also were deposited on the cooler pads made it impossible to differentiate the water treatment effects on scale deposition.

INTERPRETATIONS: Magnetically treated water apparently affects the dissolved salt concentration of cooling water used in greenhouses. Their significance in regard to scaling of the pads needs further investigation, however.

FUTURE PLANS: Continue studies on the effects of magnetic water conditioners on greenhouse cooling water. Quantify the extent of salt and scale deposits on cooler pads to better manage greenhouse cooling operation.

COOPERATORS: None

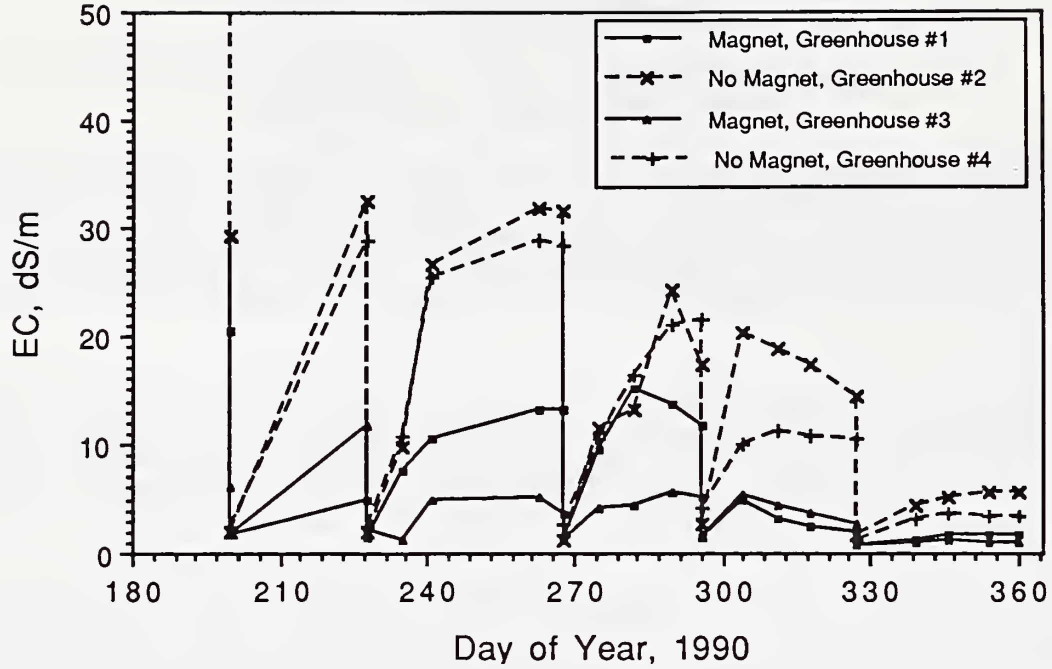

Figure 1. Electrical conductivity of treated and untreated sump water for 1990.

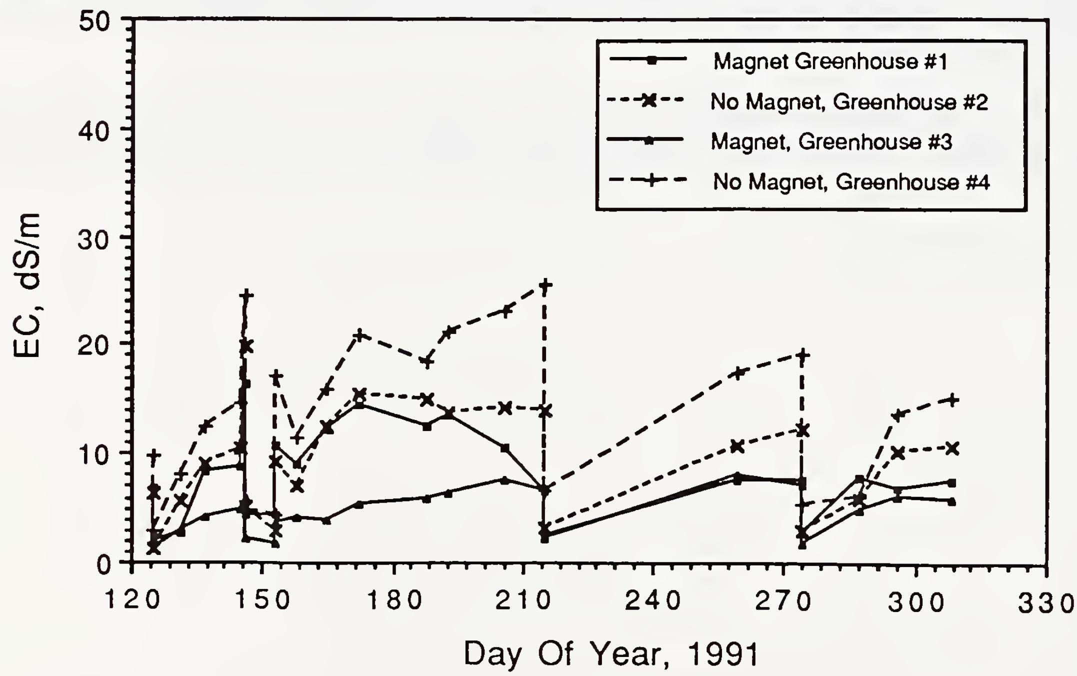

Figure 2. Electrical conductivity of treated and untreated sump water for 1991.

GROUNDWATER QUALITY PROTECTION

WATER REUSE

H. Bouwer, Chief Engineer

PROBLEM: There is a very rapidly increasing interest in the use of sewage effluent. There are two main reasons for this interest: (1) In water short areas, sewage effluent is an important water resource that can be used for various municipal and agricultural purposes, and (2) increasingly stringent standards for discharging sewage effluent into streams or other surface water make sewage treatment so costly that local reuse becomes economically attractive. Municipal uses of sewage effluent include urban irrigation (parks, playgrounds, sports fields, golf courses, cemeteries, yards of private homes), cooling water for power plants and other industrial applications, toilet flushing, and, as a last resort, potable use. Agricultural use is primarily irrigation, either straight from the sewage treatment plant or after discharge into streams or irrigation canals and dilution with other water. Water reuse requires treatment of the sewage effluent so that the quality of the final effluent meets the quality criteria of the intended use. The greater the human exposure and ingestion of the wastewater, the more stringent the treatment requirements are.

APPROACH: The work essentially consists of technology transfer through responses to invitations to speak, write, and give advice, and to serve on committees. Results from twenty years of previous work on groundwater recharge with sewage effluent are used to show the role that groundwater recharge and recovery of the water from the aquifer can play in the treatment and the reuse of sewage effluent. These results are supplemented with results from other, ongoing projects such as those in Southern California and in Arizona (Tucson). Papers have been written and presented on the technology of groundwater recharge, on the treatment benefits obtained with groundwater recharge and recovery systems (soil-aquifer treatment or SAT), on the role of SAT in the treatment of wastewater for reuse (including potable use), and on the benefits of water reuse (for example, in mitigating competition problems for water by urban and agricultural uses).

FINDINGS: Groundwater recharge with sewage effluent and recovery of the recharge water from the aquifer is a simple, economical method to provide treatment and storage of waste water for reuse, saving on the order of 50% of the cost of in-plant advanced wastewater treatment processes. The water after SAT generally is suitable as such for unrestricted irrigation and recreation. With additional treatment, it can also be used for potable purposes. SAT also provides seasonal underground storage of the water, which is important where there are seasonal changes in the demand for the wastewater, such as irrigation. Last but not least, SAT enhances the aesthetics of water reuse, especially for potable purposes, because it breaks the pipe-to-pipe connection of direct wastewater recycling.

INTERPRETATION: Use of wastewater is good water conservation because it reduces demands for fresh water, prevents waste of good water to oceans or other bodies of water from where it cannot be recovered, and protects the quality of streams, lakes, or other surface water from wastewater discharges.

FUTURE PLANS: Continue to be responsive to requests for speaking, writing and giving advice on groundwater recharge, water reuse, and related issues. Continue working with committees on groundwater recharge and water reuse, including a recently appointed committee of the Water Science and Technology Board of the National Research Council, National Academy of Sciences.

CONCENTRATION AND PREFERENTIAL FLOW EFFECTS ON PESTICIDE RATE AND TRANSPORT IN SOILS

R. C. Rice, Agricultural Engineer and G. C. Auer, Physical Science Technician

PROBLEM: The widespread detection of pesticides in groundwater indicates our inability to accurately predict the fate and transport of chemicals in soils. Two factors that have a strong influence on pesticide fate are pesticide concentration and preferential flow. Either factor may result in accelerated chemical transport. High pesticide concentration can occur through misuse of pesticides, excess applications in turn rows, or spills. Preferential flow, which usually is thought to occur in macropores, has been observed in unstructured field soils under unsaturated as well as saturated flow conditions.

The object of this project is to determine the effect of high concentrations of pesticides on transport and degradation under field conditions.

APPROACH: Experimental plots were established on uncropped Mohall sandy loam soil (fine loamy, mixed, hyperthermic Typic Haplargid) at the Maricopa Agricultural Center, University of Arizona. The soil had been bare for at least 24 months. The experimental field was divided into sixteen 6 x 6 m plots. All plots and a buffer area were flood irrigated with two 15 cm irrigations prior to herbicide and tracer application. Three herbicides, bromacil, napropamide, and prometryn were applied at two different rates and replicated three times. The three herbicides were applied in combination to the same plot for both application rates. In addition, each herbicide was applied to 3 separate plots at the high rate. This was to determine if there was any interference between herbicides at the high rates. The application rates and plot location is shown in Table 1. A conservative tracer was applied to each plot with the herbicide. The tracers used were 2,6-diflurobenzoic acid (2,6-DFBA), pentafluorobenzoic acid (PFBA), o-trifluoromethylbenzoic acid (o-TFMBA) and m-trifluoromethyl benzoic acid (m-TFMBA). A separate tracer/herbicide formulation was prepared for each plot. The four conservative tracers were selected so that no two adjacent plots received identical tracers. The herbicide/tracer solution was sprayed on the soil by making 5 to 6 passes with a hand-held spray rig over each subplot.

Evaporation was determined using the energy balance method from meteorological data recorded at the site. (Rice and Jackson, 1985)

Soil samples from three sites in each of the 15 treated plots were obtained during a two day period commencing 70 days after application. A second sampling was obtained 310 days after the first pesticide application. For the top 90 cm, cores were taken using a 5.0 cm I.D. sample tube equipped with a plastic insert. The sample tube was driven into the soil to a depth of 90 cm and removed. The plastic tube containing the soil core was removed and sealed. Below 90 cm, the samples were taken at 30 cm intervals to a depth of 2.7 m using a 2.0 cm I.D. Veihmyer tube. Each 30-cm samples was placed in a resealable plastic bag and the bag placed in a ice chest. Upon return to the laboratory, the 90 cm sample was divided into six-10 cm subsamples (10 to 60 cm) and one 30 cm sample (60-90 cm). All samples were then subdivided into two groups. One sample was used for water content and tracer analysis, and the other sample for herbicide analysis.

Potassium bromide was applied to all plots 268 days after the first tracer application. A second soil sampling was conducted 53 days later.

For tracer analysis, a 10-g subsample of each core at field moisture content was extracted with 10-ml of water by shaking for 20 minutes in a 50-ml polypropylene centrifuge tube. After centrifugation and filtering, the tracers were quantified using an HPLC technique. A separate 10-g sample was taken at the same time for gravimetric water content determination. The pesticide analysis was conducted by Robert Bowman at the New Mexico Institute of Mining and Technology.

FINDINGS: Depth-concentration relationships were determined for each hole and each tracer. Velocity and dispersion coefficients were determined for each hole by fitting the data to the one dimensional convection-dispersion equation using the non-linear least squares inversion method assuming resident

concentration values for the tracers. The velocity and dispersion coefficients for each site are shown in table 1 for the first sampling and in table 2 for the second sampling. The variance in solute velocity was considerably less than in previous experiments located in the same area. The velocity of the water based on water balance criteria was 1.57 cm/day. The tracer velocity for the same time period was 2.69 cm/day or 1.71 times greater than the water balance velocity. The relative velocity ratio is similar to that measured in previous years at the same location. All of the pesticides were either degraded or moved beyond the sampling depth as of the second sampling date.

INTERPRETATION: Interpretation of the data is continuing. Preferential flow did occur and was about 1.7 times faster than would be calculated from the water balance. This data further corroborates the presence of preferential flow under intermittent flood conditions. The pesticide degradation and/or mobility was greater than anticipated. Predicting preferential flow and incorporation into solute transport models will improve our ability to reduce or minimize groundwater contamination and improve management practices for more efficient use of water, pesticides, and fertilizer.

FUTURE PLANS: The field portion and laboratory analysis of the pesticide data has been complected. Pesticide transport models using laboratory data on sorption and degradation are being validated. The laboratory based information will be related to the behavior in the field.

COOPERATORS: R. S. Bowman NM inst of Mining and Technology, BARD project

REFERENCES: Rice R.C., and Jackson, R.D. 1985. Spatial distribution of evaporation from bare soil. Proc. Advances in Evaporation Symp. ASAE, Chicago, IL., 16-17 Dec. 1985. p. 447-453.

Table 1. Tracer velocity and dispersion coefficients for first sampling.

plot	VELOCITY cm/day hole 1	hole 2	hole 3	average
1	3.56	0.99	3.26	2.60
2	2.39	2.35	2.91	2.55
3	3.90	3.03	3.31	3.41
4	2.37	2.59	3.31	2.76
5	2.19	3.17	2.97	2.78
6	1.89	2.51	2.54	2.31
7	1.90	4.25	2.02	2.72
8	2.27	2.32	2.74	2.45
10	2.03	2.31	> 4.06	2.80
11	1.58	2.44	2.28	2.10
12	2.86	2.56	2.55	2.66
13	1.76	3.13	2.41	2.44
14	2.44	3.27	3.51	3.07
15	3.05	2.89	3.64	3.20
16	3.67	2.01	> 3.87	2.52
all plots				2.69

plot	DISPERSION COEFFICIENT cm^2/day hole 1	hole 2	hole 3	average
1	1.50	2.74	0.96	1.55
2	2.06	5.90	3.08	3.26
3	4.79	2.37	3.96	3.53
4	0.90	2.28	6.26	3.36
5	3.02	2.07	1.85	2.99
6	1.56	2.65	2.39	3.15
7	2.60	19.87	1.46	7.73
8	0.43	10.69	13.83	8.24
10	1.88	2.69	----	3.83
11	4.27	2.02	3.54	5.21
12	1.35	1.00	1.80	4.04
13	1.04	4.49	1.30	4.96
14	0.78	1.20	2.45	4.61
15	5.52	3.52	3.08	6.78
16	0.75	0.94	----	11.99
all plots				3.86

Table 2. Tracer velocity and dispersion coefficients for second sampling.

plot	hole 1	hole 2	hole 3	average
1	4.46	2.61	3.06	3.37
2	3.91	3.28	2.31	3.17
3	2.41	2.16	2.28	2.28
4	2.65	2.77	2.73	2.72
5	2.42	3.19	2.49	2.70
6	1.94	1.41	1.45	1.60
7	1.86	2.28	1.04	1.73
8	1.84	2.15	1.44	1.81
9	1.94	1.65	1.39	1.66
10	2.10	2.14	1.45	1.90
11	2.39	2.10	1.69	2.06
12	1.96	1.74	1.72	1.81
13	2.22	2.76	2.49	2.49
14	2.87	2.73	1.90	2.50
15	2.09	3.37	2.37	2.61
all plots				2.29

DISPERSION COEFFICIENT cm^2/day

plot	hole 1	hole 2	hole 3	average
1	29.51	3.27	4.24	12.34
2	7.51	6.50	5.00	6.34
3	3.16	2.65	4.00	3.27
4	3.74	2.38	2.67	2.93
5	5.00	5.20	2.89	4.36
6	16.54	4.64	4.00	8.39
7	5.07	9.55	4.00	6.21
8	1.50	7.04	5.89	4.81
9	4.21	2.16	16.70	7.69
10	5.58	7.31	4.51	5.80
11	4.76	8.70	2.55	5.34
12	1.37	2.78	1.79	1.98
13	1.75	3.12	3.39	2.76
14	4.51	6.65	2.92	4.69
15	3.40	3.78	2.10	3.09
all plots				5.33

SIMULATION OF CHEMICAL TRANSPORT WITH SURFACE IRRIGATION FLOWS

T.S. Strelkoff, Research Hydraulic Engineer; F.J. Adamsen, Soil Scientist; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Irrigation management influences the quality of both surface and groundwater supplies. Chemigation introduces agricultural chemicals into the irrigation water. Initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, chlorinated organic compounds, and heavy metals, for example, brought to farm fields in the course of agricultural operations, and occurring naturally, selenium, for example, all can be transported to surface or subsurface water supplies by the movement of irrigation water, to the detriment both of human consumers of the water resource and wildlife dependent on these bodies of water.

The transport, transformation, and ultimate fate of chemical components of the irrigation water depends on the quantities of water remaining in the root zone after the irrigation, the quantities running off the end of the fields into drainage ditches and canals, and the quantities that continue to percolate through the soil, entering eventually either a ground-water aquifer or a river fed from ground-water seepage. The chemical and physical reactions between the water, the soil medium, and the particular chemicals involved significantly influence the transformation and ultimate fate of the chemical constituents.

Preferential flow, fingering of the water front advancing downward through the soil medium, arises both as the result of nonhomogeneous soil, with worm and root channels, and layering of soils, with a layer of low permeability overlying one of great permeability. This results in more rapid transport of waterborne constituents to the ground-water table.

In the porous subsurface medium, many existing models view variation in only one dimension, the vertical, assuming no movement parallel to the stream flow. However, *interflow* is known to occur, especially on steep slopes, and in fact provides the principle means of transport of ground water, along with its chemical constituents, into surface streams.

The goal of this research effort is a predictive tool, a computer model, capable of simulating the response of a given agricultural field and its geologic site to one or another irrigation-management practice. Computer simulations would allow swift comparisons amongst various trial management modes in a program to seek optimum solutions. This would make possible recommendations on the basis of environmental considerations as well as upon water conservation and crop yield.

APPROACH: Many of the individual physical and chemical processes, especially inorganic salt exchanges, that together determine the outcome of one or another management practice are well understood, if imperfectly quantified. Other reactions, especially between organic constituents and individual soil compositions are still under investigation by soil chemists, within ARS and other research agencies. The physical processes of fluid turbulence are known to play a role in the suspension of sediments into the surface stream, a state in which maximum reacting surface area is made available to the water-soil chemical exchange. A first-order prediction of turbulence distribution can be made on the basis of existing phenomenological approaches. Newer computer-oriented turbulence models can, in principle, be coupled to equations describing the variations in temporal averages of velocity and pressure in the surface stream.

In any event, the combined influence of the various interactions is too complex to allow simple calculation of expected results. The mathematical equations describing these processes, however, can be combined into a mathematical model of the irrigation.

The current emphasis is on assembly of the team which will be working in the development of such a model, and in reviewing the literature for existing mathematical modeling techniques pertinent to related problems.

FINDINGS: The project is too new to have developed any results. Preliminary investigations suggest several potential lines of attack. An idealized, microscopic approach views the soil grains as cylinders. A finite-element solution, with weighing functions of the Petro-Galerkin type, simulates the flow, with attendant turbulent fluctuations, in the surface stream, and also in the interstices between cylinders. Well below the soil-surface/irrigation-stream interface, volume averages of flow variables approximate Darcy flow. If the latter is assumed to persist to the interface, a slip condition on boundary velocity, typically determined empirically, is required for the surface stream. The first trial envisaged is an empirical relation developed for plane Poiseuille flow (between parallel plates), the lower portion of which is in Darcy flow, and the upper portion in Navier-Stokes flow.

A second technique is based on macroscopic advection-diffusion equations for non-isothermal saturated-unsaturated groundwater flows, incorporating empirical adsorption-resorption reactions as source-sink terms. This approach, like traditional solutions of saturated-unsaturated flow in porous media, requires empirically determined soil properties. The flow equations in the surface stream and in the soil can be solved first, independently of the chemical-reaction equations. The results of this solution provide the framework for the chemical transformation and transport equations.

At the front of an advancing surge, the complicated *rolling* motion of the water is expected to scour the soil surface and force material into suspension, much as in the case of sand scooped into the body of a breaking wave at the beach. The traditional one-dimensional assumptions in the frontal zone -- little velocity variation in the longitudinal direction, and vertical variation unchanged from that in gradually varied flow in the bulk of the wave -- most likely do not provide sufficient detail to predict the probably intense local water-quality-influencing phenomena in the wave front.

Each individual water-borne chemical component and soil mineral is understood to have a unique adsorption and resorption description. It is not clear whether data on these obtained from soil columns under static conditions will continue to hold up under flowing conditions. Presently, only physical verification, perhaps under laboratory conditions, is proposed to deal with this issue.

INTERPRETATION: A clear indication of the preliminary findings is that a major concern will be the circumscription of a problem simple enough to yield results and complex enough that the results be useful. The total effort will have to be staged, with the grossest findings developed first. Every stage is expected to contribute to our ability to judge the influence of surface-irrigation management on the degradation of the water resource.

FUTURE PLANS: Graduate students prepared to approach the microscopic and macroscopic aspects of the problem are currently being selected by the cooperating researcher at the University of Michigan. Local efforts will concentrate on establishing the adsorption/resorption relations for the models, and in coupling model results with existing surface-irrigation models, reported under a separate research project.

COOPERATORS: N.D. Katopodes, University of Michigan

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

R. C. Rice, Agricultural Engineer; F. J. Adamsen, Soil Scientist;
D. J. Hunsaker, Agricultural Engineer; H. Bouwer, Research Hydraulic Engineer;
and F. S. Nakayama, Research Chemist

PROBLEM: Contributions to groundwater pollution by deep percolating irrigation waters could be minimized and/or eliminated by the development and application of existing and new technologies. However, this requires a better understanding of chemical and water transport in the soil environment. In the arid southwest more than 75% of the water used is for irrigating crops. Prudent operation of irrigation systems to apply this water can minimize the movement of water and chemicals below the root zone, thus controlling groundwater pollution. Theoretically, irrigating at 100% efficiency will lead to zero deep percolation and keep water and chemicals in the crop root zone. Crop leaching requirements could be met when crops are not being grown, when most of the applied nutrient chemicals have been used by the crop. However, because of spatial variability and preferential flow of water in the soil profile, 100% irrigation efficiency may still produce some deep percolation and transport of chemicals to the groundwater.

The objective of this research is to determine the movement of water and nitrogen fertilizer in the soil profile when irrigating at or near 100% irrigation efficiency and to develop best management practices to reduce groundwater degradation.

APPROACH: Research will be conducted through a series of experiments to evaluate the 100% irrigation efficiency theory. Cotton was grown using level basin flood irrigation in 1991. Nitrogen fertilizer was applied with the irrigation water (chemigation). The experimental design was a complete randomized block with six fertilizer-water application treatments and three replications. Each experimental plot was 81 m^2. A different conservative tracer was applied with each fertilizer application. Nitrogen status of the crop was correlated with leaf chlorophyll content as determined with a chlorophyll meter. This is a relatively new technique that may allow determination of nitrogen stress in the crop and when and how much fertilizer to apply. Water movement in the soil profile was characterized with soil water content and tracer analysis. Evapotranspiration was estimated from energy balance techniques using meteorological data collected at the site.

Experimental treatments were 1) a "standard procedure" where irrigation and fertilizer applications are scheduled according to current farm practices with 100% irrigation efficiency and 2) with 80% irrigation efficiency; 3) surface applied fertilizer applications are scheduled according to residual soil, petiole NO 3-N feedback and leaf chlorophyll content with 100% irrigation efficiency and 4) with 80% irrigation efficiency; 5) irrigation water applied fertilizer applications (chemigation) are scheduled as in treatment 3 with 100% irrigation efficiency and 6) with 80% irrigation efficiency.

FINDINGS: Unfortunately one of the tracers had a toxic effect on the cotton. Two days after the m-triflurobenzoic acid tracer was applied with the water, curling of the leaves was noted. Two plots that did not receive the tracer did not show the effect. The effect was more noticeable on the new growth and was evident through most of the growing season. The effect did subside in late August however, few bolls were set and production was severely limited. Because of this factor, no cotton yields were obtained. Dry matter was obtained but the effect of the toxic reaction was much greater than the effect of the different nitrogen and irrigation efficiency treatments. Soil samples were obtained and are being analyzed to evaluate the depth of tracer movement.

INTERPRETATION: This research will demonstrate how much of the applied fertilizer can be confined to the root zone under 100% irrigation efficiency during the growing season. The extensive and intensive field measurements will provide information for determining preferential water and chemical flow, spatial

variability, irrigation uniformity, efficiency, scheduling, evapotranspiration and best irrigation management practices to minimize transport of nitrates to the groundwater. In addition, soil solution (nitrogen) and soil air (carbon dioxide) composition measurements will provide data for evaluating chemical equilibrium and for estimating nitrogen and water balances needed in various models under the various irrigation regimes. Although crop production is not part of the primary objective, such information will also be obtained. The combined data can be used to test existing models for water and chemical movement and crop yield.

FUTURE PLANS: The experiments will be repeated using wheat. An additional treatment of 20% deficit irrigation will be included. A separate greenhouse experiment will be conducted on the phytotoxic effects of the benzoic acid tracers on wheat and cotton.

COOPERATORS: Dr. J.E. Watson, University of Arizona, Maricopa Agricultural Center

NITROGEN BUDGETS OF IRRIGATED CROPS USING NITROGEN-15 UNDER HIGH EFFICIENCY IRRIGATION

F. J. Adamsen, Soil Scientist; R. C. Rice, Agricultural Engineer;
F. S. Nakayama, Research Chemist; D. J. Hunsaker, Agricultural Engineer; and
H. Bouwer, Research Hydraulic Engineer

PROBLEM: Nitrate is the pollutant most commonly found in groundwater. The contribution of nitrate to groundwater pollution carried by deep percolating irrigation water could be reduced or eliminated by the development of existing and new technologies. This requires a better understanding of the total nitrogen required by the crops produced and the timing of nitrogen uptake as well as chemical and water transport in the soil environment. Careful timing of fertilizer applications and prudent operation of irrigation systems to reduce the amount of water lost below the rooting zone can reduce the movement of water and chemicals to groundwater. Theoretically, irrigating at 100% efficiency and carefully controlling fertilizer amounts and timing of applications should lead to no deep percolation and no fertilizer leaching losses. Crop leaching requirements could be met when soil nitrate levels were lowest. However, because of spatial variability, preferential flow, and incomplete uptake of nitrogen by the crop, 100% irrigation efficiency and optimum nitrogen management may still produce some deep percolation and transport of nitrate to groundwater.

APPROACH: Research will be conducted through a series of experiments to evaluate irrigation efficiency and nitrogen management practices. Wheat will be grown using level-basin flood irrigation during the first year. Future experiments will use cotton as the crop and other irrigation methods such as drip and sprinkler irrigation. The experimental design will be a complete randomized block with six fertilizer-water application treatments and three replications. Experimental plots will be approximately 81 m^2 in size. A different conservative tracer will be applied with each irrigation and nitrogen-15 tagged fertilizer will be applied to three micro-plots in each main plot. Micro-plots will be approximate 1 m^2. This will allow a complete water and nitrogen balance, including the amount of nitrogen removed with the harvested crop, percolation losses and volatile losses. The nitrogen status of the crop as determined by tissue analyses will be correlated with the leaf chlorophyll content as determined by a chlorophyll meter. Chlorophyll measurements may allow a rapid cost effective method for determining the nitrogen status of a crop in real time and may be useful in determining the amount and timing of fertilizer nitrogen applications. Water movement in the soil profile will be characterized by soil water content and tracer analysis. Evapotranspiration will be estimated from energy balance techniques, with verification from soil moisture measurements.

Experimental treatments will include 1) a "standard" irrigation and fertilizer management procedure where irrigation and fertilizer applications are scheduled according to current farm practice with 100% irrigation efficiency, 2) same as treatment 1 except with 80% irrigation efficiency, 3) same as treatment 1 except with a deficit irrigation equivalent to 120% irrigation efficiency, 4) irrigation water applied fertilizer application (chemigation) scheduled according to residual soil, petiole NO_3-N feedback, and leaf chlorophyll content with 100% irrigation efficiency, 5) same as treatment 4 except with 80% irrigation efficiency, and 6) same as treatment 4 except with a deficit irrigation equivalent to 120% irrigation efficiency.

INTERPRETATION: This research will demonstrate how much of the applied fertilizer can be confined to the root zone under 100% efficiency irrigation during the growing season, and optimum fertilizer management. The field measurements will provide information on nitrogen use efficiency under varying water management systems, preferential water and chemical flow, irrigation uniformity, spatial variability, and best irrigation and nitrogen management practices to reduce transport of nitrate to groundwater. Although crop production is not part of the primary objective, such information will also be obtained. The combined data can be used to test existing models for water and chemical movement and crop yield.

COOPERATORS: Dr. J. E. Watson, The University of Arizona, Maricopa Agricultural Center

PHYTOTOXIC EFFECTS OF BENZOIC ACID TRACERS ON WHEAT AND COTTON

F. J. Adamsen, Soil Scientist; R. C. Rice, Agricultural Engineer; and
D. J. Hunsaker, Agricultural Engineer

PROBLEM: A valuable tool for following the movement of water in soils has been the use of fluorinated benzoic acids as conservative tracers. Using different tracers makes it possible to follow the movement of separate water fronts applied to the same site. Most of the work with benzoic acid tracers has been in systems without plants. When used in the field, tracers applied in solutions made from technical grade material contain 15% impurities. The tracers are similar chemically to a number of herbicides and therefore the tracers and the impurities are potentially phytotoxic. Application of technical grade *m*-(trifluoromethyl) benzoic acid (*m*-TFMBA) to cotton in 1991 resulted in deformed leaves and aborted bolls. The purpose of this study is to determine the potential toxicity of *m*-TFMBA, *o*-(trifluoromethyl)benzoic acid (*o*-TFMBA), 2,6-difluorobenzoic acid (2,6-DFBA), and pentafluorobenzoic acid (PFBA) to wheat and cotton.

APPROACH: Wheat and cotton were planted in the greenhouse in commercial potting mix in November 1991. Benzoic acid derivatives were added as solutions of technical grade material and as solutions of reagent grade material at a concentration of 30 mg L^{-1}. Additional chemical treatments used were a no tracer check and 120 mg L^{-1} Br^- as KBr. All solutions were prepared in tap water. The concentrations used are comparable to those found in irrigation water when the tracers are applied in the field. Treatments were applied at planting and after full expansion of the second true leaf. Chemicals were added to the soil and did not come in contact with the plant leaves. Treatments were replicated ten times. Dry matter production will be determined after plants have been allowed to develop after being treated. In addition any physical symptoms will be noted and described. A second trial will be planted in Mohall sandy loam soil from the Maricopa Agriculture Center. The same chemical treatments will be applied in second experiment.

INTERPRETATION: This research will help determine which if any of the tracers currently used to follow water movement in soil can be used with crops and which crops may be sensitive to the tracers. This study should determine whether any phytotoxic effects are the result of a tracer or the result of impurities in the technical grade materials. Extending the use of benzoic acid tracers to cropped systems will provide powerful tool for determining water movement in soil-plant systems.

FUTURE PLANS: The data collection portion of this study should be completed in early 1992, and data analysis should be completed shortly thereafter. Preliminary results will be applied to field studies currently underway. Final results will be complied and reported in journal format. If other crops are evaluated in the future, similar trials will be needed for each crop of interest.

COOPERATORS: None.

QUASI-POINT SOURCES OF AGRICULTURAL GROUNDWATER CONTAMINATION

QUASI-POINT SOURCES OF AGRICULTURAL GROUND-WATER CONTAMINATION

H. Bouwer, Chief Engineer and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Ground water contamination from quasi-point sources of pesticides and nitrate pose problems for farmsteads in the United States. Sources of such contamination include backflow of pesticides into wells during chemigation practices, chemical storage facilities, chemical mixing facilities, cleaning facilities, septic tanks, feedlots and manure disposal areas. There is a need to develop methodologies to aid the Soil Conservation Service, Experiment Stations, and EPA and other regulatory personnel in determining if the chemical pollution observed in a well originates from quasi-point sources or non-point sources.

APPROACH: A suite of pumping tests techniques will be developed to determine the disappearance characteristics of chemicals of interest. These tests will provide "disappearance type curves" of such chemicals. In practice, these curves would be compared with temporal data on the changes in contaminant concentrations during pumping of suspect wells to ascertain if the origin of the contaminant is a non-point or quasi-point source. When contamination has been detected, and before remediation activities may begin, the boundaries of the contaminant plume must be defined and the origins of the contamination must be determined. The proposed approach is to produce a method of inferring the nature of the source from the behavior of the contaminant concentration when a well is being pumped. The distribution of contaminant in ground water at any moment can be characterized by a three dimensional picture of the concentration associated with every point in space. Determining this distribution from the behavior of the contaminant when the well is pumped is a difficult problem in that the observed change in concentration with time is not the unique property of a single distribution but could be the result of a number of combinations of chemical and hydrogeologic factors. The interaction of these factors and their effect on the change in contaminant concentration during pumping needs to be investigated.

The ability to detect differences in pollutant source with well pump tests will have to be verified through field studies. Sites with known pollution sources will have to be identified and the procedures tested.

FINDINGS: Near-well models are being developed to simulate the behavior of hydraulic head and contaminant concentrations to pumping stress. For simple geometries, the models are analytic and, for more complex geometries such as multi-layering, the models will be numerical. The principal product of these models are disappearance type curves. A disappearance type curve represents the draw-down and concentration behavior of a well to extraction stress. Concentration change behavior reflect the point-quasi-point or areal source nature of the contaminant. The concentration changes are masked to some extent by the geologic and hydrologic regime. The effects of these regimes are being investigated in the analysis. Of particular interest is the effect of multi-layering which produces effects that make distinguishing between source types difficult. Disappearance curves for point, quasi-point and non-point sources for organic contaminants (NAPLs) in layers of various thicknesses at the top of the aquifer are being investigated.

INTERPRETATION: The analyses provide a better understanding of the origins of nitrate and pesticide contamination. Knowledge of the origins of the contamination will enable the application of specific remediation activities tailored to the distribution properties of the contaminant.

FUTURE PLANS: Point source and quasi-point source contamination remediation will be investigated through the application of simulation models to determine zones of capture, concentration reduction and plume motion. A three dimensional particle tracker will be used to illustrate and delineate advective flow.

A three dimensional transport model will be used for dispersive flows. Adsorption processes will be considered. In addition, the influence of cracks, biopores and other macropores on the efficiency and effectiveness of remediation of point and quasi-point source contamination in the vadose zone will be examined. Because water moving through macropores travels more quickly to the water table, essentially bypassing the majority of the porous material, the resulting effective adsorption coefficients may differ significantly from those of the bulk porous material. Of particular interest is the placement and frequency of sampling of monitoring wells, the distribution and pumpage of the extraction wells, and the feedback mechanism to mesh model predictions and real time and space data collection activities to improve parameter estimation.

During 1992, field sites will be located where pump tests can be conducted. Preferably, the initial sites will be geologically/hydrologically simple with known pollution conditions and appropriate observation wells for verification. Cooperation with other ARS locations with appropriate field sites is anticipated.

COOPERATORS: Thomas Maddock III, L.G. Wilson and Randy L. Bassett, Department of Hydrology and Water Resources, University of Arizona, Charles A. Onstad, Morris, MN.

PREDICTING EFFECTS OF INCREASING ATMOSPHERIC CO_2 AND CLIMATE CHANGE ON YIELD AND WATER USE OF CROPS

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON GROWTH AND YIELD OF COTTON

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P. J. Pinter, Jr., Research Biologist; and
Robert L. LaMorte, Engineering Technician

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such global environmental changes are likely to have profound effects on future crop productivity. Therefore, a field experiment was conducted whose main objective was to determine the direct effects of elevated CO_2 on cotton growth and yield.

APPROACH: The free-air CO_2 enrichment (FACE) approach was used. Four toroidal plenum rings of 22 m diameter constructed from 12" irrigation pipe were placed in a cotton field at The University of Arizona Maricopa Agricultural Center, Maricopa, Arizona, shortly after planting. The rings had 2.5 m high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching control rings at ambient CO_2 but with no air flow were also installed the field. This was actually the third year of FACE experiments on cotton, starting in 1989. Additionally in 1990 and 1991, the rings (plots) were split, so half of each ring was well-watered while the other half was water-stressed, the irrigations being applied through a sub-surface drip system.

FINDINGS: The relative increase in biomass production and in boll yield are plotted in Figure 1 for all three years of the FACE experiments. Obviously, the elevated CO_2 concentration greatly stimulated cotton growth and yield. Averaging over wet and dry treatments and the three years, at 550 μL/L biomass production increased 31% and boll yield increased 56%. In 1990, there was less stimulation by CO_2 in the dry plots than in the wet, but in 1991, there was no significant difference between the wet and dry plots in their response to CO_2.

INTERPRETATION: The findings illustrated in Figure 1 suggest that the increasing atmospheric CO_2 concentration will greatly increase cotton production, so long as any accompanying changes in climate are not too adverse. Moreover, the CO_2 concentration is projected to increase far above the 550 μL/L used here. At a near-doubling to 650 μL/L, the regression lines in Figure 1 suggest biomass and boll yields will increase by 46 and 84%, respectively.

Also shown in Figure 1 are the regression lines obtained previously from open-top CO_2 enrichment chamber experiments in 1983-87. The biomass and boll yield increases observed here are somewhat less and more, respectively, than the 60% increases obtained in those experiments. Considering the degree of scatter in the data, however, it appears that for the most part, the results from the FACE and the open-top chamber experiments are fairly consistent. Therefore, either method can be used to determine the <u>relative</u> effects of CO_2 enrichment on growth and yield. However, because the FACE approach has no walls that alter the environment, the <u>absolute</u> growth measurements obtained from the FACE plots have to be regarded as more representative of future field conditions.

FUTURE PLANS: The FACE approach has now been used for three years on cotton in Arizona and for two years in Mississippi before that. It is felt that we now have adequate data for cotton, and that it is time to move on to another crop. Considering that wheat is an important world-wide food crop, that it grows well in Arizona as a common rotation crop with cotton, that some controlled-environment data are already available, and that some progress is already being made on wheat growth models, it has been decided to commence FACE experiments on wheat starting in the fall of 1992. In the meantime, all of the cotton data need to be analyzed and manuscripts written. A test of the drip irrigation system is being conducted with wheat this 1991-92 winter.

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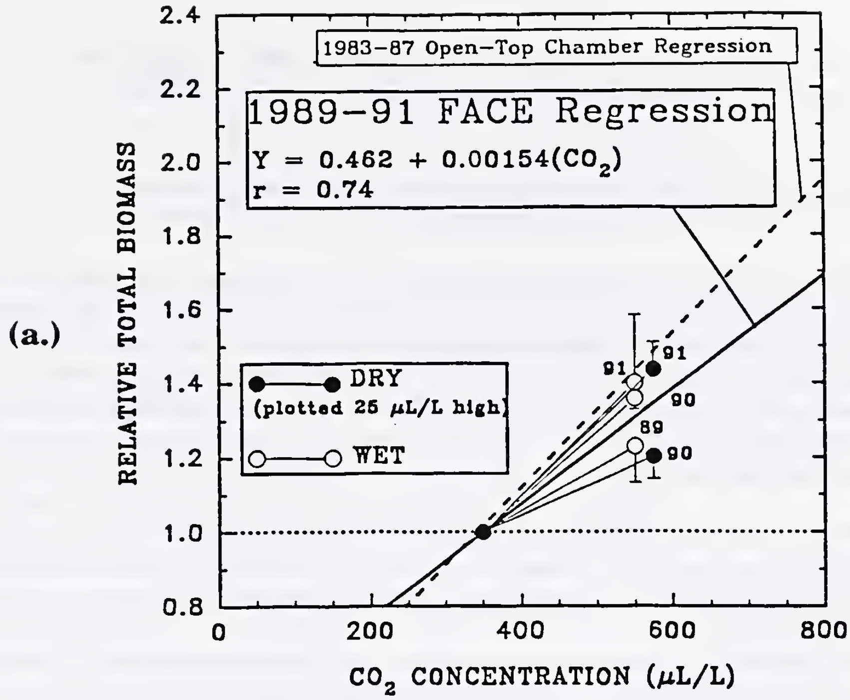

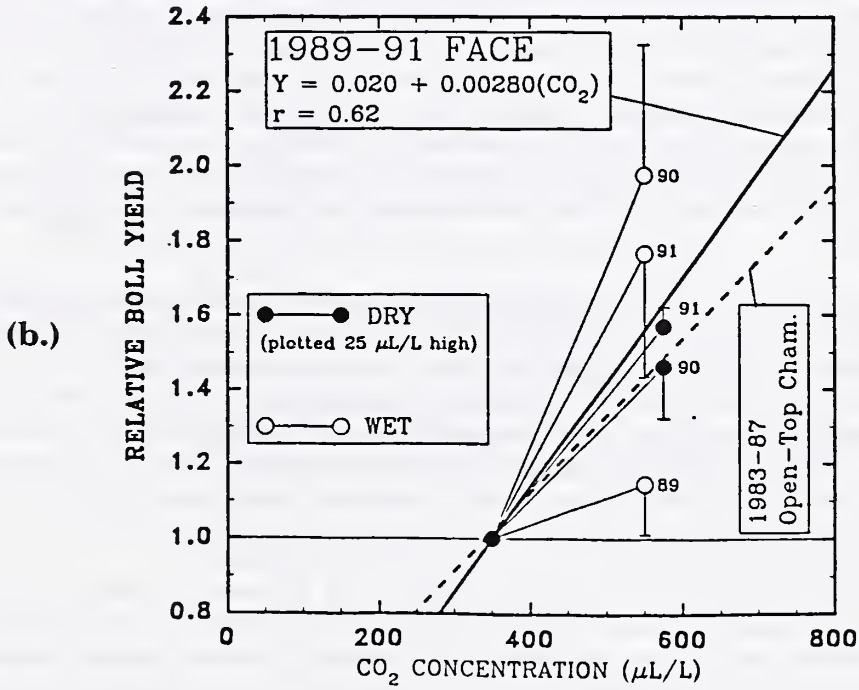

Figure 1. Relative increase in biomass (a) and relative increase in boll yield (b) of FACE plots with respect to control plots as a function of CO_2 concentration in the free-air CO_2 enrichment (FACE) experiments at Maricopa, Arizona. As indicated, the experiments were conducted from 1989-91 and there were both well-watered (wet) and water-stress (dry) treatments. The regression line obtained from prior (1983-1987) open-top CO_2 enrichment chamber experiments is also presented. To reduce clutter, only the upper or lower standard error bars are plotted and the dry treatment points are offset by 25 μL/L on the same regression line.

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON EVAPOTRANSPIRATION OF COTTON

B. A. Kimball, Supervisory Soil Scientist;
D. J. Hunsaker, Agricultural Engineer; and
W. A. Dugas, Micrometeorologist, Texas A&M University

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (ET), which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. The objective of this experiment was to evaluate the effects of elevated CO_2 on the ET of cotton.

APPROACH: The evapotranspiration measurements were one component of the much larger Free-Air CO_2 Enrichment (FACE) project, which sought to determine the effects of elevated CO_2 on plant growth, yield, and many physiological processes, as well as water use. Four toroidal plenum rings of 22 m diameter constructed from 12" irrigation pipe were placed in a cotton field at The University of Arizona Maricopa Agricultural Center, Maricopa, Arizona, shortly after planting. The rings had 2.5 m high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching control rings at ambient CO_2 but with no air flow were also installed the field. Additionally in 1990 and 1991, the rings (plots) were split, so half of each ring was well-watered while the other half was water-stressed, the irrigations being applied through a sub-surface drip system.

The determination of ET was done with three approaches: (1) Residual in the energy balance, (2) Residual in the water balance, and (3) stem flow gauges. With the energy balance approach, ET was calculated as the difference between net radiation, R_n, soil heat flux, G, and sensible heat flux: $ET = R_n - G - H$. R_n was measured with net radiometers and G with soil heat flux plates. H was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. The air temperature was measured with an aspirated psychrometer, and the crop surface temperature was measured with infrared thermometers mounted above each plot.

With the water balance approach, ET was calculated as the difference between the amount of water applied, as metered through the drip irrigation system, and the change in storage of soil moisture, as measured with neutron scattering apparatus for depths below 20 cm and time-domain reflectometry for the surface soil. With the stem flow gauge approach, commercially-made stem flow gauges were installed on cotton plants selected to be representative of the typical plants in the field. The technique provides a direct measure of transpiration, T, but in this subsurface-drip-irrigated field, soil evaporation, E, was a small component of ET, as shown in an accompanying report.

FINDINGS: The data for 1991 are still being analyzed. Some preliminary data from 1990 are presented in Figure 1. The upper graph (Fig. 1a) shows the daily ET measurements for four days in September 1990, as determined from the energy balance. There appears to be little effect of the FACE or irrigation

treatments on ET for these days, as determined by the energy balance approach. The middle graph (Fig. 1b) shows the ET of the FACE and control plots as determined from the water balance approach for most of the 1990 season. Again there does not appear to much effect of the FACE treatment on ET. The bottom graph (Fig. 1c) shows the ratio of FACE to control T measured with the stem flow gauges for about six weeks during 1990. On those days marked with an asterisk, there was a significant difference in sap flow between the FACE and control plots. In the wet plots, FACE appears to have reduced T by 90 to 75%.

INTERPRETATION: Much data remain to be analyzed, so no definitive statements can be made about the effects of FACE on ET. The energy and water balance approaches both suggest that there was no significant effect of FACE on ET. However, both techniques suffer from the fact that ET is the residual difference among several other components, and therefore, errors of measurement in the other terms accumulate in this residual term. The stem flow measurements, on the other hand, suggest that FACE does reduce T (and ET because E is small). The data are scattered and the gauges did not work properly all the time. Yet on those days when all appeared to be correct, these direct measurements of plant water loss show a reduction in transpiration caused by the FACE treatment.

FUTURE PLANS: The first priority is to complete analysis of the data obtained in 1991, as well as 1990. Then, when the FACE project moves to wheat in the fall of 1992, these measurements will be repeated.

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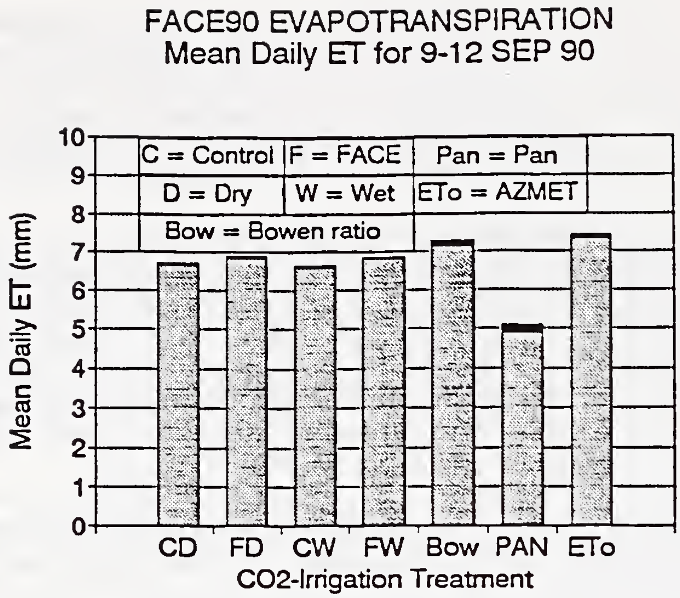

Figure 1. Mean daily evapotranspiration for 9-12 September 1990, as determined from the residual in the energy balance. "BOW" is from Bowen ratio apparatus near the control-wet plot. "PAN" is pan evaporation from a Class A pan partially within the control-wet canopy. "ETo" is potential evaporation from the AZMET system.

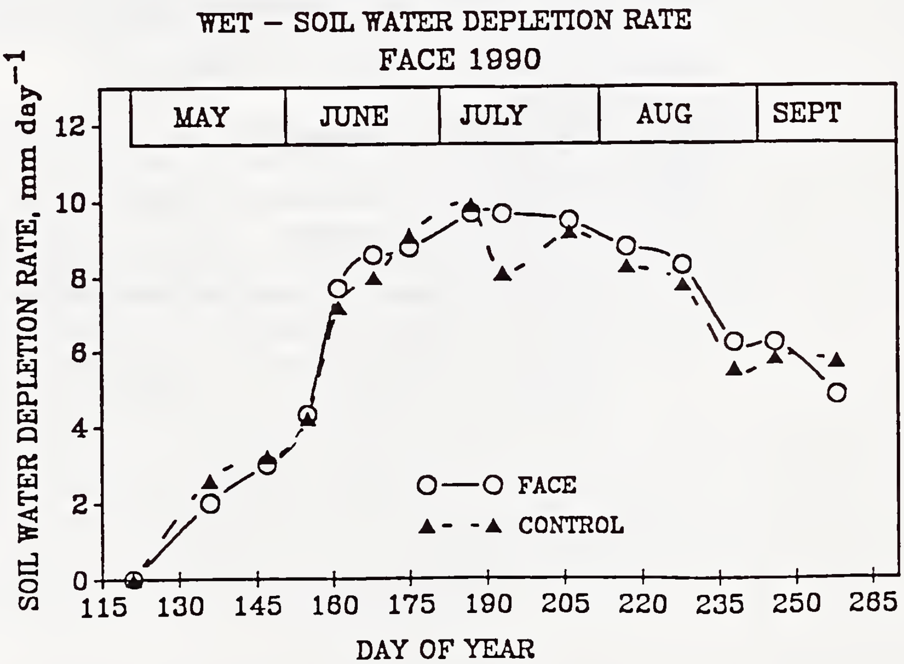

Figure 2. Soil water depletion rate from the wet FACE and control plots versus day of year for 1990.

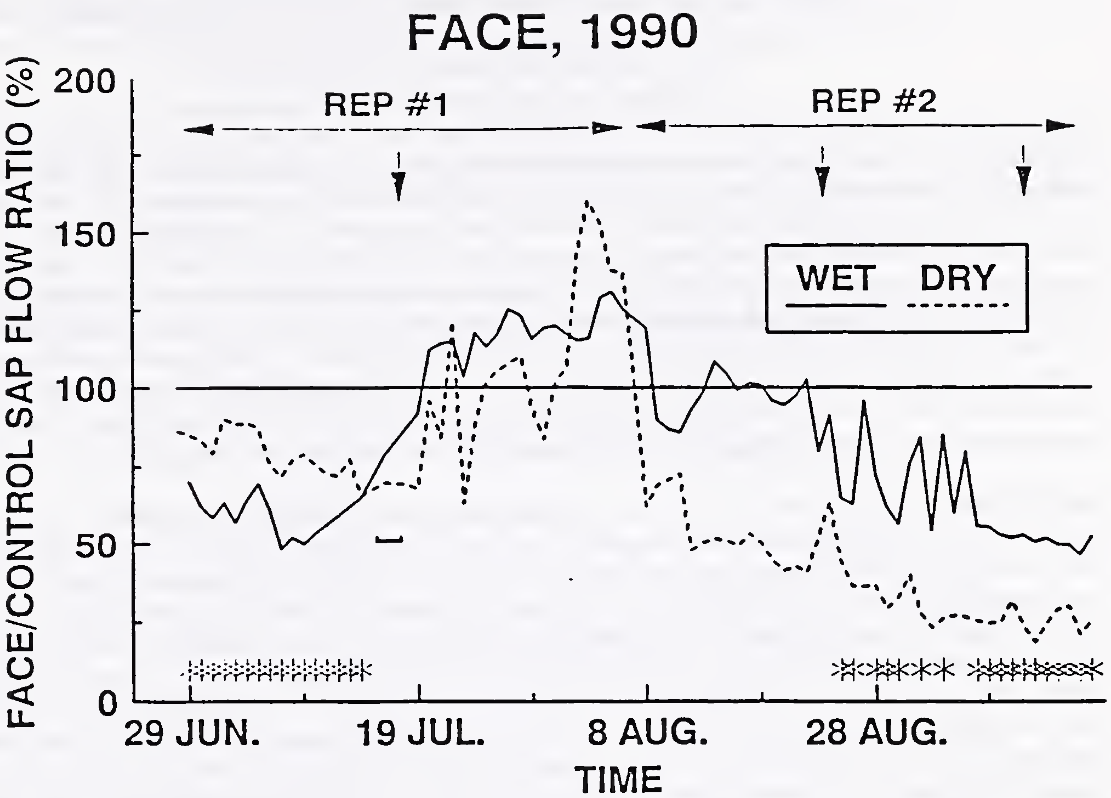

Figure 3. Ratio of average daily sap flow (n = 1 to 3) from FACE and control CO_2 treatments for full (WET) and 75% (DRY) irrigation treatments in 1990. Period of sap flow measurements in replicates 1 and 2 are shown by arrows. Asterisks denote days when there was a significant difference ($\alpha = 0.05$, one-tailed) between the average sap flow (an average of wet and dry treatments, n = 2 to 6 for each treatment) in the FACE and the control CO_2 treatments. Vertical arrows denote days when sap flow gauges were changed or a new plant was selected for measurement in a replicate and rotated bracket denotes the three days when the CO_2 concentration in the FACE treatment was at the control (ambient) concentration.

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON SOIL EVAPORATION BENEATH A COTTON CANOPY

B. A. Kimball, Supervisory Soil Scientist and
M. S. Johnson, Physical Science Aide

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be directly affected is plant transpiration (T), which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. Consequently, another component that could be indirectly affected is evaporation (E) directly from the soil surface because: (1) the changed plant growth produces changes in shading of the soil surface and/or in root extraction or (2) the lowered stomatal conductance and reduced leaf transpiration allows more energy to be available for soil evaporation. The objective of this experiment was to evaluate the effects of elevated CO_2 on soil evaporation (E) beneath a cotton canopy.

APPROACH: The soil evaporation measurements were one component of the much larger Free-Air CO_2 Enrichment (FACE) project, which sought to determine the effects of elevated CO_2 on plant growth, yield, and many physiological processes, as well as water use. Four toroidal plenum rings of 22 m diameter constructed from 12" irrigation pipe were placed in a cotton field at The University of Arizona Maricopa Agricultural Center, Maricopa, Arizona, shortly after planting. The rings had 2.5 m high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching control rings at ambient CO_2 but with no air flow were also installed the field. Additionally in 1991, the rings (plots) were split, so half of each ring was well-watered while the other half was water-stressed, the irrigations being applied through a sub-surface drip system.

Soil evaporation was determined using the microlysimeter method of Boast and Robertson (C.W. Boast and T.M. Robertson, 1982. A "micro-lysimeter" method for determining evaporation from bare soil: Description and laboratory evaluation. Soil Sci. Soc. Am. Proc. 46:689-696.), except we used longer acrylic cylinders rather than metal in order to reduce heat conduction from the surface to lower depths. Each microlysimeter was a thin-walled cylinder 76 mm dia. by 152.4 mm long. The technique consists of (a) driving the cylinder into the soil, (b) removing the soil-filled cylinder from the field, (c) closing the bottom with a rubber stopper to make it water tight, (d) determining the mass of the microlysimeter, (e) replacing it in the field with its top surface even with the surrounding soil, (f) waiting for evaporation to occur while it is exposed to environmental conditions for a period of time (typically 1 day), (g) again removing it from the field, and finally (h) again determining its mass. Eight microlysimeters were installed in each wet plot of replicates 1 and 2 only. They were in pairs at 0, 25, 50, and 75 cm from the east-west oriented cotton rows.

FINDINGS: The soil evaporation rates are presented in Figure 1 versus day of year. Although there is some scatter, it appears that an excellent data set was obtained. E was consistently lower in the FACE plots, averaging 18% less for the data available over the whole season. Moreover, a paired "t" test showed this difference was highly significant.

INTERPRETATION: We surmise that greater shading or possibly greater root extraction near the soil surface reduced evaporation (E) from the soil surface. Any greater energy available for E from any CO_2-induced reduction in leaf T did not manifest itself or was less than the shading/root effects.

However, the values of E measured in this subsurface-irrigated field were on the order of only about 7% of evapotranspiration (ET). Therefore, any direct effects of CO_2 on plant T are more likely to predominate in determining any ET changes in the hydrologic cycle in the future. Nevertheless, these measurements of E were necessary to complement other measurements of T by stem flow gauges in the determination of total ET.

FUTURE PLANS: When the FACE project changes to wheat in the fall of 1992, it is planned to determine soil evaporation under the wheat canopy using the microlysimeter technique.

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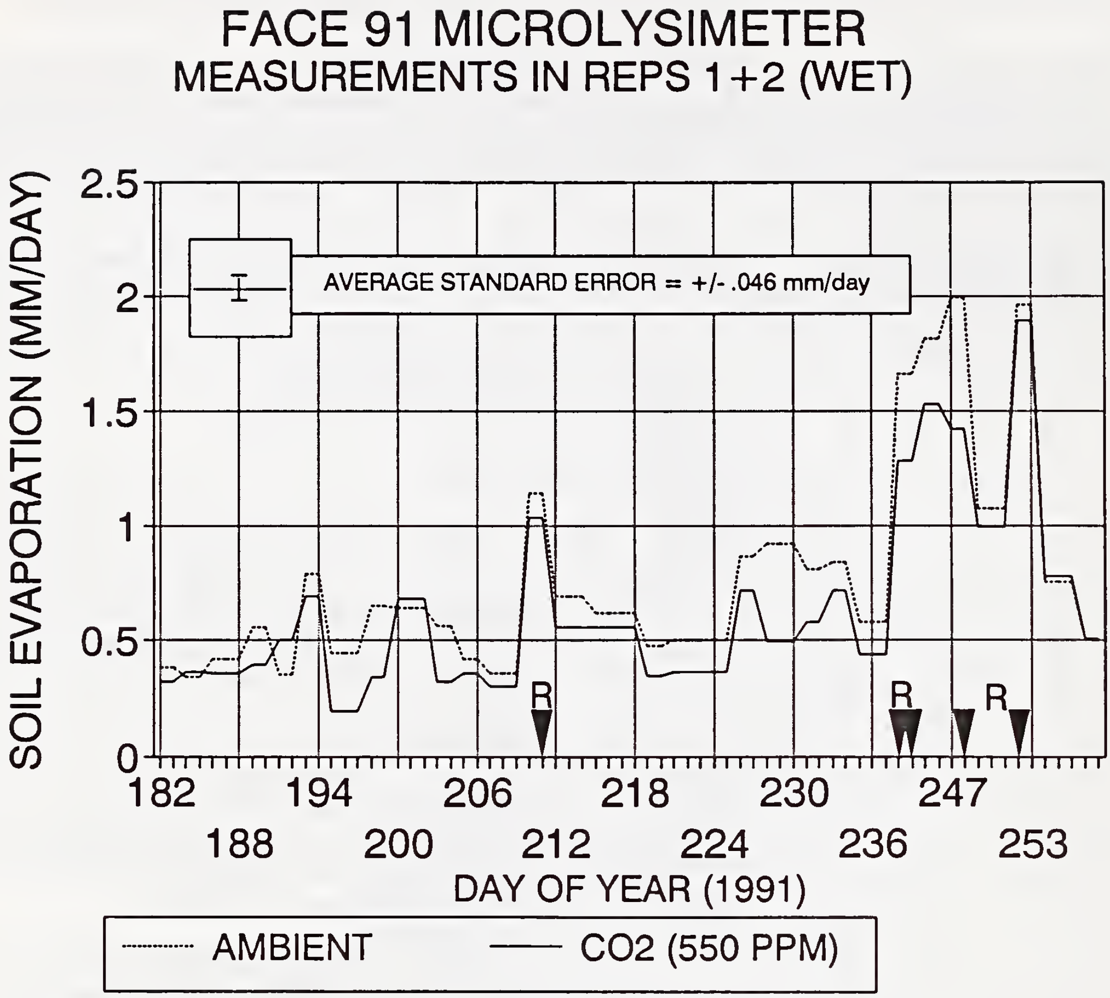


Figure 1. Soil evaporation rates determined beneath cotton canopies enriched to 550 μL/L of CO_2 in FACE and in ambient control plots versus day of year. The "R"s indicate days of rain greater than 1 mm.

EFFECTS OF FREE AIR CO_2 ENRICHMENT ON LIGHT USE EFFICIENCY OF COTTON

Paul J. Pinter, Jr., Research Biologist and
Bruce A. Kimball, Supervisory Soil Scientist

PROBLEM: The capture of solar energy by plants and the ensuing transformation of that energy into biomass are fundamental to understanding the dynamics of carbon flow in our planet's ecosystems. The efficiency of this conversion can be quantified in a simple, yet useful parameter known as light use efficiency or LUE. Often expressed as dry phytomass produced per unit of solar energy absorbed by the plants, LUE reflects the consequence of various environmental perturbations on the overall growth response of plant communities. We studied the effects of supra-ambient atmospheric CO_2 concentrations and water stress on the LUE of cotton during 3 consecutive years of Free Air Carbon dioxide Enrichment experiments (FACE) conducted in Arizona. A critical aspect of this research focused on developing remote sensing techniques to quantify the amount of solar energy absorbed by the canopy throughout the entire growing season.

APPROACH: Cotton (*Gossypium hirsutum*, L. var Deltapine) was grown in field experiments at the The University of Arizona Maricopa Agricultural Center beginning in 1989. Plants were exposed to ambient and elevated daytime CO_2 concentrations (ca. 370 and 550 μmol/mol, respectively) from shortly after seedling emergence until mid-September. In all 3 years, a "wet" irrigation treatment provided sufficient water to meet consumptive demand. A "dry" treatment supplying water at rates approximately two thirds of seasonal requirements was initiated during early boll filling period in 1990: the dry treatment started 3 weeks after emergence in 1991. Irrigation was delivered via subsurface drip tubing buried at 10 cm. Plant density was ~100,000 ha^{-1}; row orientation was E-W and spaced at 1 m intervals. Agronomic properties were estimated every 7 to 14 days by destructive harvest of every third plant from 3 separate meters of row. Above and below ground plant components were dried to obtain estimates of total dry matter produced.

A 1-meter long, line quantum sensor (LiCor, LI-191A) was used to estimate the fraction (*f*) of photosynthetically active radiation (PAR, 400-700 nm) captured by the canopy in 4 replicates of each treatment. Measurements were conducted during a 2 h period (1100 to 1300h, MST) on 4 days in 1990 and 7 in 1991. All observations were made relative to incoming PAR (I_o) obtained at the same time with the sensor horizontally positioned above the canopy. Fractional canopy transmittance ($f\,T_{PARc} = T_{PARc}/I_o$) was acquired with the line quantum sensor at the soil surface and perpendicular to the row direction. Fractional canopy reflectance ($f\,R_{PARc} = R_{PARc}/I_o$) was measured by inverting the sensor over the top of the canopy, perpendicular to row direction. The fractional reflectance of soil beneath the canopy was estimated as the product of canopy transmittance and the PAR reflected from bare soil ($f\,R_{PARs} = f\,T_{PARc} * R_{PARs}/I_o$). A simple light balance equation was then used to compute the fraction of PAR absorbed by the canopy:

$$f\,A_{PARc} = 1.0 - f\,T_{PARc} - f\,R_{PARc} + f\,R_{PARs} \qquad \text{(Eqn 1).}$$

The amount of PAR absorbed by the canopy (A_{PARc}, MJ m^{-2} day^{-1}) was calculated as the product of midday $f\,A_{PARc}$ and the daily sum of incident PAR estimated from global solar radiation measured at the Maricopa Agricultural Center AZMET station. A_{PARc} was accumulated from plant emergence until harvest during each growing season.

Canopy reflectances were measured using a handheld Exotech Model 100BX radiometer (15° fov); the red (0.61 to 0.68μm) and NIR (0.79 to 0.89μm) wavebands were used in this analysis. Data were collected 1 to 7 times each week during the season. The measurement sequence which required 25-35 minutes to complete, was centered on a morning time period corresponding to a constant solar zenith angle of 45°. Only data obtained under clear sky conditions were used in this study. During 1989, 48 measurements were taken across a 12-row transect in each plot. In subsequent years, 24 measurements were made across 6-row transects in each plot.

Radiometer voltages were recorded on a Polycorder (Omnidata International, Inc.). Reflectance factors were calculated as the ratio of reflected light measured over the cotton to incident energy inferred

from a time-based interpolation of data collected at ~15 min. intervals from a calibrated, painted $BaSO_4$ reference panel. Correction factors were applied to the panel data to compensate for its non-lambertian properties. The normalized difference vegetation index (NDVI), was then computed as the difference between NIR and red reflectance factors divided by their sum:

$$NDVI = (NIR-Red) / (NIR+Red) \qquad \text{(eqn 2).}$$

FINDINGS: We observed large differences in biomass which were related to CO_2 level and irrigation treatment. Figure 1 shows data acquired during the 1991 growing season. The highest biomass consistently occurred at 550 ppm CO_2 and well-watered conditions. In 1990 and 1991 the lowest biomass was found in the ambient CO_2/dry irrigation combination. The fA_{PARc} was also strongly influenced by the experimental treatments. Examples of the data obtained using the line quantum sensor in 1991 are shown in Figure 2. The FACE treatment showed significant early to mid-season enhancement of fA_{PARc}. The effect that water stress has on the development of the plants' light capturing apparatus is also evident in these data. Although the energy absorbed by plants tended to level off late in the season at approximately 90-95% for the wetter irrigation regime, water stress reduced fA_{PARc} to 85% or less.

A significant correlation was found between measured fA_{PARc} and NDVI (Fig. 3). This relationship which appeared similar in 1990 and 1991 and was independent of CO_2 and water treatments enabled fA_{PARc} prediction throughout each growing season using frequent and easily obtained measurements of canopy reflectance. During 1991 (Fig. 4) differences in predicted fA_{PARc} between CO_2 treatments were quite evident; divergence of wet and dry treatments first became noticeable in mid-June (DOY 165), 25 days after the differential irrigations were begun.

The NDVI was also used to assess A_{PARc} throughout each growing season, using incident PAR estimates derived from daily global solar radiation totals. The net biomass accretion between successive destructive samples was then divided by A_{PARc} which was accumulated over the same time period, yielding an estimate of LUE for each growth interval. Seasonal LUE values varied from 1.26 to 2.24 g biomass MJ A_{PARc}^{-1}, depending on year, water stress, and CO_2 level (Fig. 5a & b). When plants were supplied with ample water, LUE averaged 1.50 gMJ^{-1} for ambient CO_2 concentrations and 1.86 gMJ^{-1} under 550 μmol/mol CO_2. Deficit irrigation reduced LUE to 1.44 and 1.77 gMJ^{-1} for ambient and FACE cotton, respectively.

INTERPRETATION: Spectral reflectance measurements provided a very effective, non-invasive method for comparing the light harvesting capabilities of vegetation canopies and integrating the amount of solar energy captured over a given time interval. Three years of data revealed that cotton develops rapidly under enhanced CO_2 concentrations, attaining complete ground cover more quickly and thus absorbing more solar radiation than canopies exposed to ambient CO_2 levels. We also found that LUE was enhanced under supra-ambient CO_2 levels. This is the first time that LUE of any plant exposed to supra-ambient CO_2 concentrations has been evaluated at the entire canopy level without the possible artifacts of chamber walls. In the well-watered irrigation treatment, a 50% increase in atmospheric CO_2 was accompanied by a 23.9% increase in cotton LUE. The 22.9% increase in LUE that was caused by extra CO_2 in the dry irrigation treatment suggests that CO_2 may have the same effect at different levels of water stress.

FUTURE PLANS: These data will be examined on a finer time scale, obtaining LUE estimates for different growth intervals during the season and thus revealing dynamics of LUE which are not readily apparent with conventional techniques. Estimates of LUE as discussed in this report will become an increasingly useful approach for comparing the response of crops to a broad range of environmental changes that might exist in the future.

COOPERATORS: University of Arizona, Brookhaven National Laboratory, Department of Energy, and Western Cotton Research Laboratory. Line quantum sensors were loaned to us by Dr. Don Wanjura, USDA/ARS Lubbock, TX. We also wish to acknowledge the services of Dr. Jack Mauney, Plant Physiologist, retired USDA/ARS, for agronomic data and cultural management of FACE. ARS Technicians Ric Rokey, Robert LaMorte, Ron Seay, Robert Anderson, Carrie Coble, Noel Rhoades, Carrie Carpenter, Elaine Hassinger and Christy McClelland assisted in various phases of data collection.

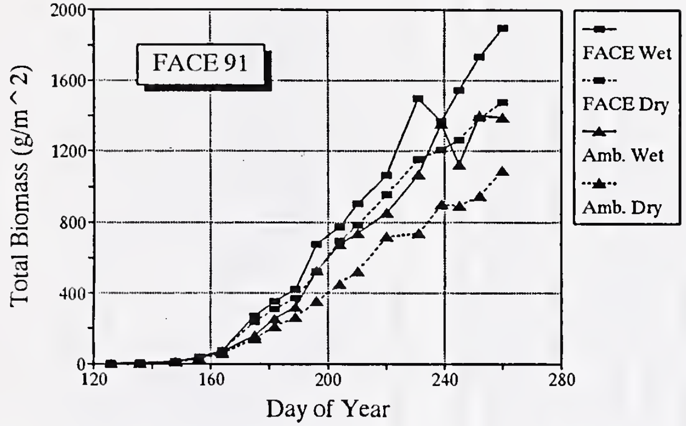


Figure 1. Total biomass measured during the 1991 FACE project in cotton. Each datum is the average of 4 replicates per treatment. Reference to FACE in the legend corresponds to 550 μmol/mol CO_2 concentration during daylight hours; Amb. corresponds to ambient CO_2 levels ($\sim$370 μmol/mol).

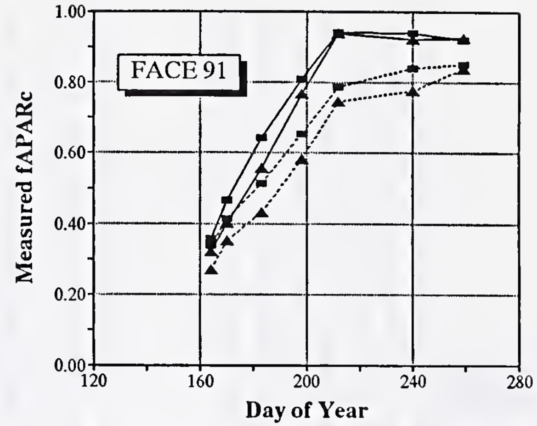


Figure 2. The fraction of photosynthetically active radiation (fA_{PARc}) absorbed by the canopies in 1991. Each datum is the average of 4 replicates; 6 observations per replicate. Data were measured with the LiCor line quantum sensor. The legend remains the same as for Fig. 1.

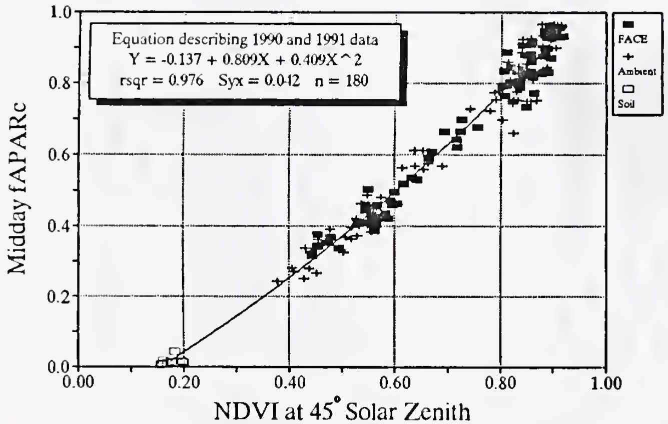


Figure 3. The relationship between midday fA_{PARc} and the normalized difference vegetation index (NDVI) measured using an Exotech radiometer. This figure includes data from 1990 and 1991.

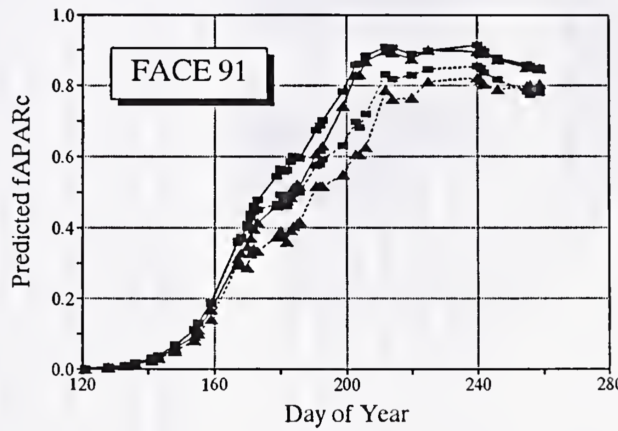
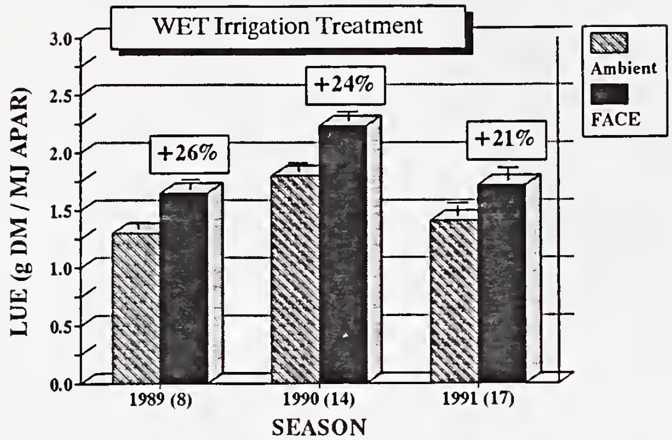


Figure 4. Seasonal trajectory of NDVI-predicted fA_{PARc} during 1991. The legend remains the same as for Fig. 1.



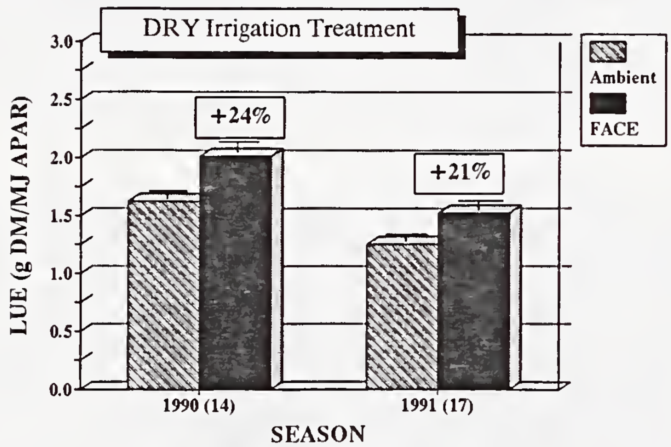


Figure 5. Average seasonal light use efficiencies for 3 years of well-watered cotton (Fig. 5a) and 2 years in which plants were subjected to water stress (Fig. 5b). Numbers included in parentheses following the year along the abscissa refer to the number of discrete biomass estimates that were made during the season. Percentage figures above the bar for the FACE treatment indicate the relative increase in LUE that was observed for the 550 μmol/mol CO_2 treatment. T's on the top of each bar show + 1 standard error of the mean.

THE INFLUENCE OF CO_2 ENRICHMENT ON CANOPY PHOTOSYNTHESIS OF COTTON

R. L. Garcia, Plant Physiologist;
B. A. Kimball, Supervisory Soil Scientist; and
G.W. Wall, Plant Physiologist

PROBLEM: Elucidating the influence of environmental conditions on crop productivity is a complex and dynamic problem; particularly when changes in global CO_2 concentrations are considered. Predictive capabilities are impaired unless fundamental mechanisms which explain how crops will respond to a changing environment are postulated and explored experimentally. Canopy gas exchange processes are central to determining the carbon balance within any plant system. Our intent, therefore, was to develop and implement an experimental protocol to ascertain the carbon dynamics of a cotton crop (Gossypium hirsutum L.) grown in ambient and CO_2 enriched aerial environments under well-watered and water-stressed soil moisture regimes.

APPROACH: Two transportable open chamber gas exchange systems were developed to measure canopy carbon dioxide exchange rates of cotton grown in the Free Air CO_2 Experiment (FACE). These chambers were designed to cover a 1.15 m length of row and were 1 m wide and 2 m tall, i.e., 2.3 m^3. For ease of handling, the chambers were constructed with extruded aluminum angle (22 mm) frame and were built in two halves. The lower half of each chamber was 1 m in height and was covered with a polyethylene envelope. The inner side of the envelope had holes of approximately 25 mm diameter spaced every 250 mm, while the outside was a solid sheet of polyethylene. This enabled a directional flow into the interior of the bottom portion of the chamber system. The upper component of the chamber system was covered with propafilm-C (ICI Americas, Inc., Wilmington, DE); a material with spectral transmission and thermal properties suitable for this application. An infrared thermometer (Everest Interscience Inc., model 4000, Fullerton, CA) and quantum sensor (LI-COR Inc., model LI-190S-1, Lincoln, NE) were mounted above the canopy inside the chamber to monitor canopy temperature and incoming photosynthetically active radiation, respectively. Air was injected into the system through the holes in the polyethylene envelope covering the lower base using a centrifugal blower at a rate of approximately 0.14 m^3 s^{-1}, while air exited through the exhaust port mounted in the upper section. A flow transducer mounted in the inlet air stream monitored flow rates through the chamber system. The 2.3 m^3 chamber required about 17 seconds for a complete air exchange in this configuration. Air temperature, relative humidity, and CO_2 concentration were monitored at the inlet and outlet ports of the system with a modified LI-COR 6200 portable photosynthesis system. Predetermined setpoints of CO_2 concentration within the chambers were maintained by adjusting a rotameter which regulated the flow of pure CO_2 being injected into the inlet port. This air stream passed through a separate infrared gas analyzer to quantify the CO_2 treatment level.

FINDINGS: Design, construction and testing of the two chamber systems was completed by July 12, 1991. Thereafter, the system was used to monitor the diurnal and temporal trends in canopy gas exchange of a cotton canopy. This included late vegetative stage, and all reproductive stages until harvest. At any one time, two separate treatments could be monitored simultaneously. The chambers were moved to new sections of the plot or to different treatments every three to five days to minimize the chamber effect on cotton growth and development. This schedule enabled the development of a database which contains a total of about 18 diurnal runs prior to terminating the experiment. Results from one such diurnal dataset are shown in Figure 1. These data illustrate the net carbon dioxide exchange rates of a cotton canopy grown under well-watered soil moisture regimes in an ambient and an aerial environment enriched to 550 uL L^{-1} CO_2. At midday a 40% increase in net canopy photosynthesis was observed in cotton canopy enriched with CO_2. Figure 2 illustrates the CO_2 response of a cotton canopy grown at ambient and

enriched CO_2. A clear separation is seen, particularly at the higher CO_2 concentrations. This suggests that a long-term acclimation occured in cotton plants grown with enriched CO_2 concentrations. Furthermore, the linear nature of this response suggest that the potential for increased productivity is still greater under higher CO_2 concentration.

INTERPRETATION: These data suggest that cotton is particularly sensitive to the atmospheric CO_2 concentration. The productivity and production efficiency of cotton should increase as global CO_2 increases.

FUTURE PLANS:

1) There are a number of improvements which could be made in the canopy gas exchange systems. One improvement involves automation of the IRGA zeroing and calibration. This should minimize problems of drift in the measurements which was a significant problem when the system was running unattended. It may also be possible to automate some of the procedures for generating CO_2 response data (as in Figure 2).

2) We will be redesigning chambers and preparing for measurements in wheat during this next season.

3) We will be incorporating leaf measurement with the canopy measurements in the future. Therefore we will be adapting a leaf system for CO_2 response studies.

4) Analyzing and publishing results.

COOPERATORS:

Brookhaven National Laboratory: G. Hendrey, K. Lewin, J. Nagy
U. S. Water Conservation Laboratory: R. LaMorte

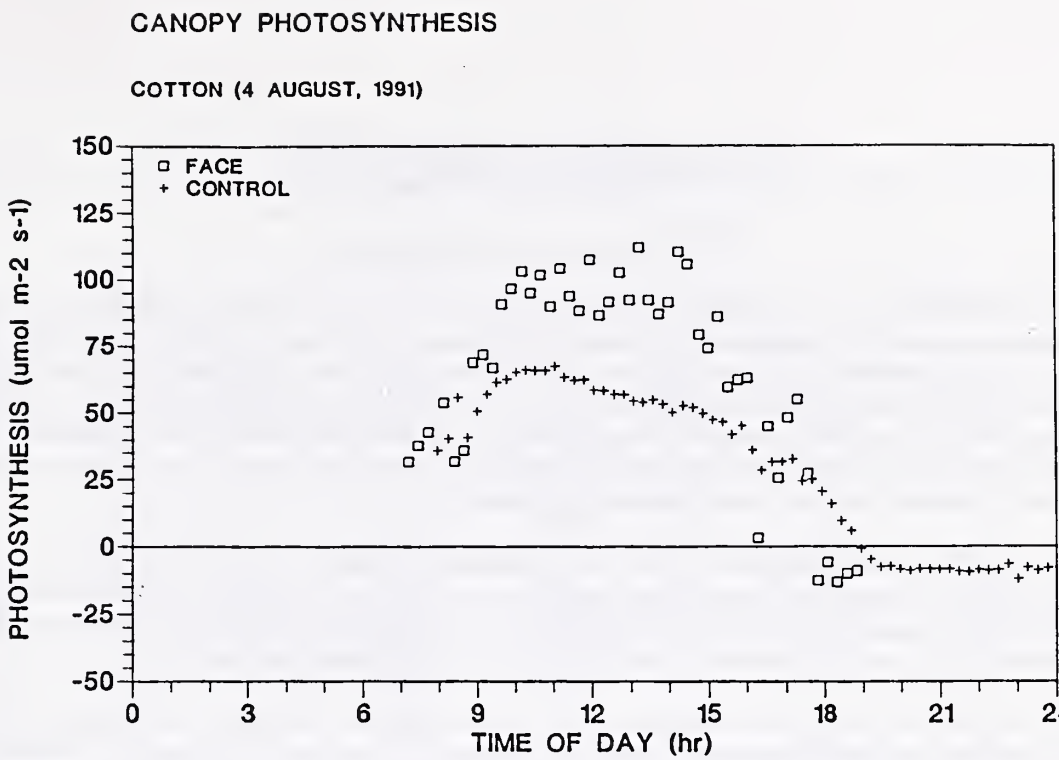


Figure 1. Diurnal course of net canopy photosynthesis for irrigated cotton grown under CO_2 enriched (FACE) and ambient (control) conditions, August 4, 1991.

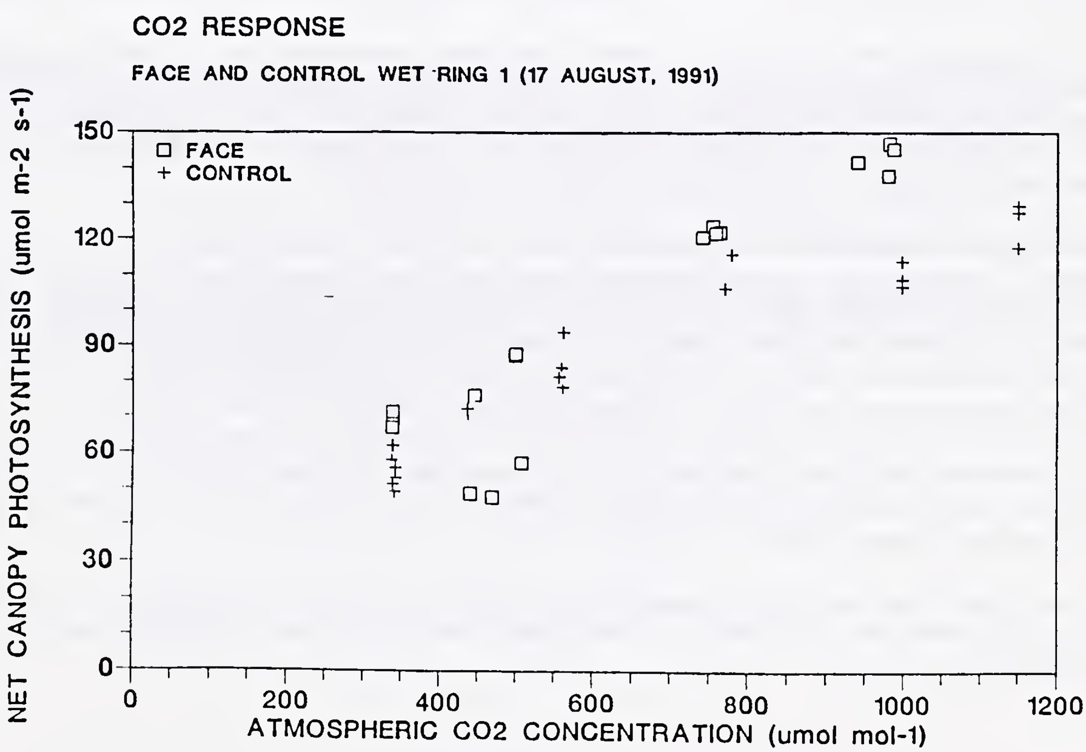


Figure 2. Net canopy photosynthesis response to atmospheric CO_2 concentration for cotton grown under CO_2 enriched (FACE) and ambient (control) conditions. Data were collected August 17, 1991, within 2 hours of midday, under clear sky conditions.

CARBON DIOXIDE FLUX IN FIELD-CO_2 ENRICHED SYSTEMS

F.S. Nakayama, Research Chemist

PROBLEM: Carbon dioxide release from the soil, the result of soil microbial and plant root activity, is an important part of the carbon balance in terrestrial systems. The rate of CO_2 release has an impact on the composition of the atmosphere. Determination of plant photosynthesis in the field using plant enclosures requires a knowledge of the soil CO_2 flux, unless steps are taken to prevent the entrance of this CO_2 into the measuring chamber. The objective of this study is to determine the soil CO_2 flux or respiration in both natural and CO_2 enriched systems for use in carbon balance models and enclosed chamber photosynthesis measuring equipment.

APPROACH: Soil carbon dioxide fluxes will be determined in conjunction with the free-air carbon dioxide enrichment system (FACE) and also the open-top enrichment chambers. Detailed measurements will also be made to ascertain the reproducibility of the sampling technique. Sampling sites will be established in the various treatment combinations of CO_2-irrigation treatments.

FINDINGS: The study site and treatments were the same in this 1991 study as the 1990 experiment at The University of Arizona Maricopa Agricultural Center, with cotton as the test crop. Soil carbon dioxide flux measurements were made in the four check and four CO_2-enriched open air release sites. The individual sampling sites also included the "wet" and "dry" water treatments. Water applications in the dry treatment were based on 2/3 of the wet treatment. Four sampling chambers for each water X CO_2 levels X four replicates were installed for a total of 64 flux sampling sites. A set of measurements was made at least once a week.

Detailed samplings involving repetitive 2-minute, continuous gas sampling for CO_2 and flux computations were made at the different sampling sites. Except for three readings that were extremely low in the 60 minute run (Fig. 1a), the fluxes obtained compared reasonably well with each other. The low values for the three sets in Figure 1a could be related to the high initial CO_2 concentration in the zero-time sample gas (Fig. 1b), which is used to calculate the flux values.

Noticeable negative fluxes were measured in the 1990 soil CO_2 flux measurements for the open-top chambers with orange trees. Periodic negative fluxes were also obtained in the FACE plots and these were originally attributed to experimental error. However, by taking continuous gas samples from the chambers, it is apparent that these negative fluxes are real values and result from a higher than normal concentration over the sampling chamber just prior to the flux measurements. An example of this type of behavior is shown in Table 1. Negative fluxes, as indicated by the asterisks, were present in one site over a 16 minute sampling period. These measurements were taken on July 8, 1991 for the check and treatment sites, when the open-air CO_2 releases were being made. After the CO_2 release was terminated as represented by the October 31, 1991 data, less fluctuation in the ambient CO_2 concentration was observed (Column 7, Table 1).

Instances of higher than normal CO_2 concentrations noted in the "check" sites indicated CO_2 drifts from the enrichment plots. The ambient carbon dioxide levels in October (394 ± 6.5) were lower than those for July (489 ± 11.6).

Table 1. Soil carbon dioxide fluxes for successive two-minute samplings.

	08 July 1991						31 October 1991		
	CHECK			CO_2 ENRICHMENT			CHECK		
	Initial CO_2 (ppm)	Final CO_2 (ppm)	Flux (uMol/ m^2/s)	Initial CO_2 (ppm)	Final CO_2 (ppm)	Flux (uMol/ m^2/s)	Initial CO_2 (ppm)	Final CO_2 (ppm)	Flux (uMol/ m^2/s)
	*665	621	-1.9	624	709	4.7	394	437	2.4
	512	604	5.2	620	673	3.0	387	432	2.4
	485	542	3.2	557	646	4.9	386	422	2.0
	488	552	3.6	668	739	4.0	406	423	0.9
	479	544	3.7	588	685	5.4	402	436	1.9
	486	530	2.5	606	689	4.6	394	435	2.3
	*679	684	-0.3	668	727	3.3	392	449	3.2
	485	551	3.7	621	663	2.3	393	434	2.2
Avg	489	554	3.6	619	691	4.0	394	434	2.2
s.d.	±11.6	±25.8	±0.9	±37.4	±31.8	±1.1	±6.5	±8.5	±0.6

*Negative flux values. Not used in calculating averages.

INTERPRETATION: Intensive soil carbon dioxide flux measurements show that the CO_2 movement could be directed into the soil in contrast to the commonly held belief that the flux is only in one direction from the soil to the atmosphere. This type of behavior cannot be determined with previous measuring systems. Such negative fluxes, however, occurs primarily when the concentration of the atmospheric CO_2 exceeds that of the "normal" concentration above the soil. Furthermore, such occurrences would be prevalent when the atmosphere above the soil is highly enriched with CO_2.

FUTURE PLANS: Complete analysis and interpretation of the field data collected in 1991. Expand experiment for determining soil carbon dioxide fluxes in other crops. Compare existing soil CO_2 flux measuring device with other methods.

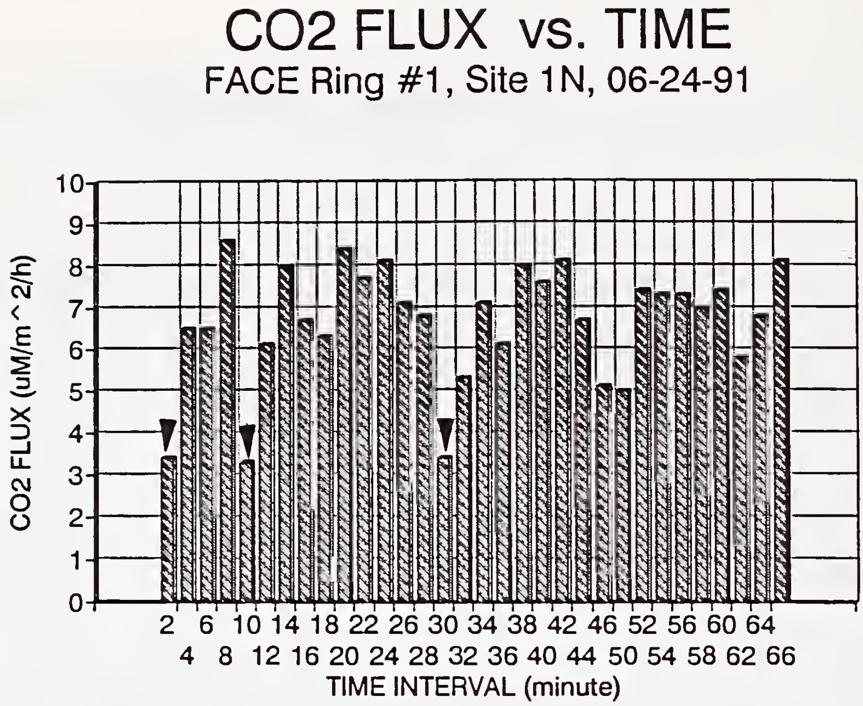


Figure 1a. Carbon dioxide fluxes for two-minute sampling intervals at one site.

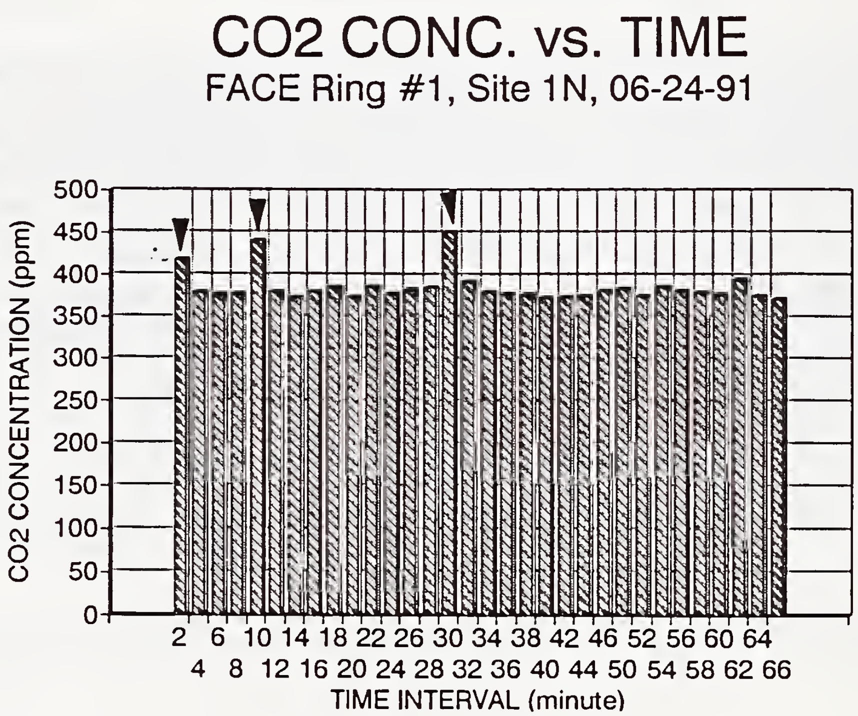


Figure 1b. Initial carbon dioxide concentration for two-minute sampling intervals at one site.

FURTHER DEVELOPMENT, VALIDATION, AND SENSITIVITY ANALYSIS OF COTCO2

G.W. Wall, Plant Physiologist and
B.A. Kimball, Supervisory Soil Scientist

PROBLEM: Global carbon dioxide concentration is increasing; therefore, a clear understanding of the major sources and sinks of CO_2 and its effect on terrestrial vegetation must be identified to ensure reliable global impact analysis. A materials-balance process-level plant simulation model sensitive to CO_2 will unravel the complexities of how global change in CO_2 and potential climate change will influence plant growth, survival, acclimation, and subsequent food and fiber production. Plant growth submodels designed to explicitly simulate the CO_2 effects on all the major first and/or second order physiological rate processes are mandatory before any large-scale global impact analysis can be undertaken. These routines should be modular in nature, thus transferable into other modeling projects when applicable. Furthermore, once developed these submodels can perform feasibility testing on plant response to potential changes in climatic conditions over a wide ecological range. This methodology is the only prospect for providing quantitative estimates of the impact of rising concentrations of greenhouse gases on global plant ecology.

APPROACH: Dr. Jeffrey Amthor developed a cotton (Gossypium hirsutum L.) simulation model, COTCO2, during his Post-Doctorate Associatship period (1988-90). He employed a systems modeling approach to quantify alterations in physiological and biochemical response in cotton to global change in CO_2 concentration. In this model organs are initiated from meristems, plant organs "grow" at their own temperature, which may be several degrees different from air temperature, leaf photosynthesis and whole plant respiration processes alter the dynamics of carbohydrate pools so long term acclimation to high CO_2 and "feedback inhibition" of photosynthesis can be addressed. The model has variable time steps depending on the particular process being evaluated; one hour for plant and aboveground environmental processes, soil processes are evaluated every minute, while variables such as phytomass accretion, leaf area index, canopy height, phenological development, and plant maps are output at the end of the daily loop.

FINDINGS: Upon entering the project in May, 1991, COTCO2 contained over 5000 lines of PC-Based OTG ANSI FORTRAN 77 code. The model had been tested on a limited scale and found to give reliable results for Phoenix, Arizona, conditions. Because of the inherent complexity of the model the computational time required for a full-season simulation was approximately 5 hours on a 386 20 MHz IBM-PC compatible computer with an Intel math co-processor. To maintain the desired level of detail while reducing execution time, a SUN Microsystems SPARCstation 2 was purchased to serve as the new developmental platform. The necessary software changes in COTCO2 have been made to make it compatible with the SUN UNIX-based operating system. This reduced the computation time 10 fold to 30 minutes for a full-season simulation. Prior to May, 1991, all input to COTCO2 were hardcoded with weather generators supplying the input meteorological data. No real-world data were used during a simulation and any modification in an input parameter required a re-compilation of the source code prior to making a run. The capability of the model to read input files from an independent source is of particular importance in model validation. Therefore, input files were developed which conform to the IBSNAT standard. Interfacing these data input files with their corresponding variables and parameters in the initialization subroutine of COTCO2 enabled a real-world simulation. This marked the beginning of the validation phase of the project. Users can now run simulations under a multitude of scenarios, i.e., environment, cultural practices, and cultivars. Experimentally derived Free Air CO_2 Experiment (FACE) (1989-91), Open-Top Chamber (1983-1987), and Soil-Plant-Atmosphere-Research (1990) databases can now be compared with simulated data.

INTERPRETATION: It is still premature to make a proper assessment of the model's ability to accurately simulate the growth and development of a cotton plant in a future CO_2-enriched world. Much work is required to determine the robustness of this model. Only through continued validation with real-world databases, and a comprehensive sensitivity analysis can the reliability of the model's predictions be ascertained. It does, however, show promise for application in larger scale global impact analyses which are designed to elucidate the long-term impact of a CO_2 enriched world on terrestrial vegetation.

FUTURE PLANS: The model validation procedure will continue and undoubtedly aid in the identification of areas where modifications in logic are required. A sensitivity analysis needs to be conducted to test the stability of the model with respect to its many parameters. Since this type of analysis requires a minimum of one hundred runs of the model to generate the appropriate statistics, a CRAY super computer will be used. We are in the process of establishing a computer account with Arizona State University and the University of Florida to gain access to a Department of Energy account on the CRAY computer located at Tallahassee, Florida, via Internet, the NFS sponsored computer network in the U.S. This link is required prior to initiation of the sensitivity analysis phase of the project. The PRISM (latin hypercube sampling) program required for this analysis has been obtained and final preparations are under way to attempt a trial run of the sensitivity analysis.

Once COTCO2 is properly validated and proves to be useful over a broad ecological range, it will provide the means to predict the impact of change in atmospheric CO_2 concentrations on global cotton production. Ultimately it will aid in strategies to mitigate adverse effects while optimizing those that are beneficial.

CO_2 ENRICHMENT OF TREES

S.B. Idso, Research Physicist and B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The continuing rise in the CO_2 content of Earth's atmosphere is believed by many people to be the most significant ecological problem ever faced by mankind, due to the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. However, this belief is largely due to a lack of knowledge of the many beneficial effects of atmospheric CO_2 enrichment on Earth's plant life. Hence, it is imperative that this other aspect of atmospheric CO_2 enrichment be elucidated, so that the public can have access to the full spectrum of information about the environmental consequences of higher-than-ambient levels of atmospheric CO_2. Only under such conditions of complete and wide-ranging understanding can the best decisions be made relative to national and international energy policies.

As forests account for two-thirds of global photosynthesis and are thus the primary player in the global biological cycling of carbon, we have chosen to concentrate on trees within this context. Specifically, we seek to determine the direct effects of atmospheric CO_2 enrichment on all aspects of their growth and development; and we hope to be able to determine the ramifications of these direct effects for global carbon sequestering, which may also be of considerable significance to the climatic impact of atmospheric CO_2 enrichment, as the biological sequestering of carbon is a major factor in determining the CO_2 concentration of the atmosphere and the ultimate level to which it may rise.

APPROACH: In July, 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. CO_2 enrichment -- to 300 ppm above ambient -- was begun in November, 1987, to two of these chambers and has continued unabated since that time. Except for this differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated at periods deemed appropriate for normal growth and fertilized as per standard procedure for young citrus trees.

In April, 1991, eight additional open-top chambers were constructed, into each of which were planted 12 new tree seedlings, including two different species of eucalyptus (*E. microtheca* and *E. polyanthemus*), the Australian bottle tree (*Brachychiton populneum*), and a conifer (*Pinus eldarica*). Two of these chambers have since been maintained at the ambient CO_2 concentration, two at 150 ppm above ambient, two at 300 ppm above ambient, and two at 450 ppm above ambient.

Numerous measurements of a number of different plant parameters have been made on the trees of both sets of chambers, some weekly, some monthly, some bi-monthly, and some annually. Results of our findings are summarized below.

FINDINGS:

(1) Idso et al. (34)* documented a 2.2-fold increase in the net photosynthesis rate of sour orange tree leaves exposed to an extra 300 ppm of CO_2 throughout the second summer of the first experiment.

(2) Idso et al. (37)* determined the above-ground trunk and branch volume of the sour orange trees exposed to the extra 300 ppm of CO_2 to be 2.8 times greater than that of the ambient-treatment trees after two full years of growth.

(3) Idso and Kimball (33)* found the fine-root biomass of the CO_2-enriched orange trees to be 2.8 times greater than that of the control trees at the 2.5-year point of the experiment.

(4) Idso and Kimball (35)* demonstrated from three years of monthly trunk crosssectional area measurements that this same high growth differential was maintained throughout all of the first three growing seasons.

* For parenthetical references, see Appendix A, Manuscripts Published or Accepted in 1991.

(5) Idso demonstrated that this large growth differential was due, in part, to the sour orange trees not closing their stomates very much in response to atmospheric CO_2 enrichment. Publication submitted to Exp. Environ. Bot.

(6) Idso (34)* marshalled evidence to suggest that naturally-occurring vegetation -- which is dominated by trees -- may be much more responsive to atmospheric CO_2 enrichment than had previously been believed.

(7) Idso (32)* demonstrated that the yearly-increasing amplitude of the atmosphere's seasonal CO_2 cycle implied that, in the mean, all of Earth's trees must respond to atmospheric CO_2 enrichment to the same degree manifest by the orange trees.

(8) Idso (33)* outlined how the above findings portend a veritable rebirth of the biosphere, with greatly augmented vegetative productivity and water use efficiency leading to a new "greening of the earth" as a direct consequence of atmospheric CO_2 enrichment.

(9) Idso and Kimball found the above-ground trunk and branch volume of the CO_2-enriched sour orange trees to possess the same size advantage at the end of three years as they did at the end of the second year of the experiment. A publication has been submitted to Agric. For. Meteorol.

(10) Idso and Kimball documented a similar sustained advantage in fine-root biomass via a bi-monthly measurement program carried out between the spring of 1990 and the spring of 1991. A publication has been submitted to Plant Cell Environ.

(11) Idso and Kimball summarized four years of net photosynthesis measurements and two years of dark respiration measurements on the sour orange trees, finding the enhancement of the former and the reduction of the latter due to atmospheric CO_2 enrichment to be stable over time and to imply a 3.8-fold amplification of tree growth for a doubling of the current atmospheric CO_2 concentration and a 6.6-fold amplification for a tripling of the air's CO_2 content. A publication has been submitted to Plant Physiol.

(12) Idso et al. demonstrated that the beneficial effects of atmospheric CO_2 enrichment on the growth rates of sour orange trees and cotton become greater and greater as light becomes more and more limiting. A publication is in preparation.

(13) In on-going analyses of data being obtained from the new tree experiment, it appears that the four other species we are studying respond to atmospheric CO_2 enrichment to essentially the same degree that the sour orange trees do.

INTERPRETATION: The implications of our findings have a direct bearing on the current debate over anthropogenic CO_2 emissions. They clearly demonstrate that CO_2 is not a pollutant, but that it is instead a very effective aerial fertilizer. So effective is it, in fact, that our results suggest that for current rates of CO_2 emissions and current amounts of forested land, the CO_2 content of the air can rise by only another 170 ppm, before the trees of the planet are so stimulated that they yearly remove all of the CO_2 that man puts into the air that does not go into the ocean. This powerful biological sequestering ability of Earth's trees suggests that the CO_2 content of the air will never rise high enough to induce significant global warming.

FUTURE PLANS: We anticipate continuing the sour orange tree experiment for several more years. We also plan to allow the small pine trees to grow for several years; and in January 1992, we plan to introduce 200 small saguaro cacti into the pine tree chambers. Long-term studies of leaf and root micronutrients, leaf chlorophyll and starch contents, and tree and soil $^{13}C/^{12}C$ ratios will also be conducted.

COOPERATORS: Institute for Biospheric Research; U. S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research

* For parenthetical references, see Appendix A, Manuscripts Published or Accepted in 1991.

EVALUATING PLANT DYNAMICS AS RELATED TO WATER CONSERVATION AND CLIMATE CHANGE USING REMOTE SENSING

USE OF REMOTELY SENSED SPECTRAL DATA FOR EVALUATION OF HYDROLOGIC PARAMETERS IN SEMIARID RANGELAND

M.S. Moran, Physical Scientist; T.R. Clarke, Physical Scientist;
P.J. Pinter, Jr., Research Biologist; and R.D. Jackson, Research Physicist

PROBLEM: To better understand regional hydrologic processes, numerical models have been developed to evaluate surface conditions and the energy/water budget and to monitor their long term evolution. Generally, these models suffer from a lack of information about states (e.g., initial soil moisture) and knowledge of the spatial and temporal distribution of critical surface characteristics. Remotely sensed spectral data can provide an indirect means of deriving the spatial distribution of quantities such as soil moisture, land cover, precipitation, vegetation status and surface energy fluxes, based on empirical and semi-empirical relationships. Most of these relationships were originally derived for agricultural sites where the vegetation was generally uniform and lush, and they cannot be easily applied to other ecosystems. If hydrological models are to be used at regional and global scales, it is necessary to reevaluate relationships between remotely-sensed data and basic hydrologic factors for heterogeneous landscapes, such as rangelands.

APPROACH: An experiment was designed to acquire remotely sensed data in the visible, near-infrared (NIR), thermal and microwave wavelengths from ground, aircraft and satellite platforms, with concurrent measurements of soil moisture and temperature, and energy and water fluxes, in a hydrologically well-instrumented semiarid rangeland watershed (Kustas et al., 1991). The experiment (dubbed Monsoon'90) was conducted at the Walnut Gulch Experimental Watershed near Tombstone, Arizona, during the dry season in June and the "monsoon" season in July and August.

The data presented here are only a fraction of the total Monsoon'90 data set. Analysis was limited to eight sites, termed METFLUX stations, containing instrumentation for measuring both general meteorological conditions and estimating the surface energy balance. Five dates were selected for this study to cover a variety of soil moisture and vegetation density conditions, while maintaining relatively cloud-free conditions during the aircraft overflights: 5 June (Day of Year 156), 28 July (DOY 209), 4 August (DOY 216), 9 August (DOY 221) and 9 September (DOY 252). For each date, a set of aircraft-based measurements of surface reflectance and temperature were compiled corresponding to a measurement time of approximately 10:00 MST. Spectral reflectance data were converted to a soil-adjusted vegetation index,

$$\mathrm{SAVI} = [(\rho_{\mathrm{NIR}}-\rho_{\mathrm{red}})/(\rho_{\mathrm{NIR}}+\rho_{\mathrm{red}}+L)](1+L), \quad (1)$$

where ρ_{NIR} and ρ_{red} are reflectance factors in near-infrared and red spectral bands, respectively, and L is the soil correction term, assumed in this case to be 0.5 (Huete, 1988).

FINDINGS: For all METFLUX sites and all possible measurement days (DOYs 156, 209, 216, 221 and 252), there was a strong correlation between surface temperature and SAVI (r^2 = 0.87), indicating the sensitivity of both values to similar surface characteristics (Figure 1).

<u>Vegetation Cover:</u> The relation between SAVI and percent vegetation cover was positive but weak for the limited period during which data were available (Figure 2). The weak relationship could be due to the difficulty of making quantitative estimates of vegetation cover at shrub- and grass-dominated sites. Vegetation is generally not uniformly distributed and conventional methods for computing vegetation cover along multiple transects can lead to bias. This situation illustrates the inherent advantage of remotely sensed data for providing integrated measurements of local and regional surface characteristics.

<u>Soil Moisture:</u> Volumetric moisture content of the soil at 0-5 cm depth was measured daily at each METFLUX site during the July-August field campaign at the peak of the monsoon season. This 2-week period provided an opportunity to examine the influence of soil moisture on spectral data during a period when vegetation growth was stable and soil moisture content was temporally and spatially variable. For DOYs 209, 216 and 221, a significant relationship was obtained between surface-air temperature and

volumetric soil moisture content (Figure 3A). The SAVI was also found to be significantly correlated with soil moisture content (r^2 = 0.80), following a more linear trend (Figure 3B). It appeared that either the SAVI was sensitive to soil background reflectance despite the soil-adjustment, or the SAVI was detecting changes in leaf turgor due to increases in available soil water.

Though an attempt was made to fit a least squares relation to these data, the shape of the curve is still uncertain. For example, contrary to the curvilinear relation reported in Figure 3A, Idso et al. (1975) found that there was a *linear* relation between T_s-T_a and volumetric soil water content (0-4 cm depth) over the range from 0 to 32%.

Daily Evaporation: An theoretically-derived expression relating daily surface evaporation (E_d) to T_s-T_a was developed by Jackson et al. (1977),

$$E_d = A - B(T_s - T_a), \tag{2}$$

where A and B are empirical constants. Empirical A and B coefficients were derived for the Walnut Gulch watershed based on a linear relation (r^2 = 0.82) between values E_d and T_s-T_a measured at eight METFLUX stations during the dry and monsoon seasons (Figure 4A). A comparison of this relation with the relation derived by Jackson et al. (1977) for irrigated wheat (Figure 4B) emphasizes the importance of reevaluating the empirical equation for rangelands conditions. If the relation for irrigated wheat (derived for T_s-T_a < 5.0) had been extrapolated for use at the Walnut Gulch site (where T_s-T_a ranged from 2.0 to 17.0), the error in estimates of E_d could have been as large as 5.5 mm/day. Nevertheless, it appears possible to develop a simple relation such as (2) that would be useful for estimating evaporation from rangelands.

INTERPRETATION: Significant relationships were found between aircraft-based spectral data and the hydrologic factors of soil moisture and daily evaporation for a semiarid rangeland site. The relations differed in shape and magnitude from those determined previously for irrigated agricultural targets. These results emphasized the need for reevaluation of common empirical equations for application to rangeland areas. Considering that rangeland covers over 30% of the earth's land surface, this reevaluation is essential in order to provide the spatially-distributed information required by hydrologic models for application on a global scale.

FUTURE PLANS: There are plans to validate this analysis using data obtained during the 1991 field season at Walnut Gulch watershed. Upon validation, these expressions will be applied using Landsat TM spectral data to produce regional maps of soil moisture and daily evaporation for input to hydrologic models developed in the U.A. Dept. of Hydrology and Water Resources.

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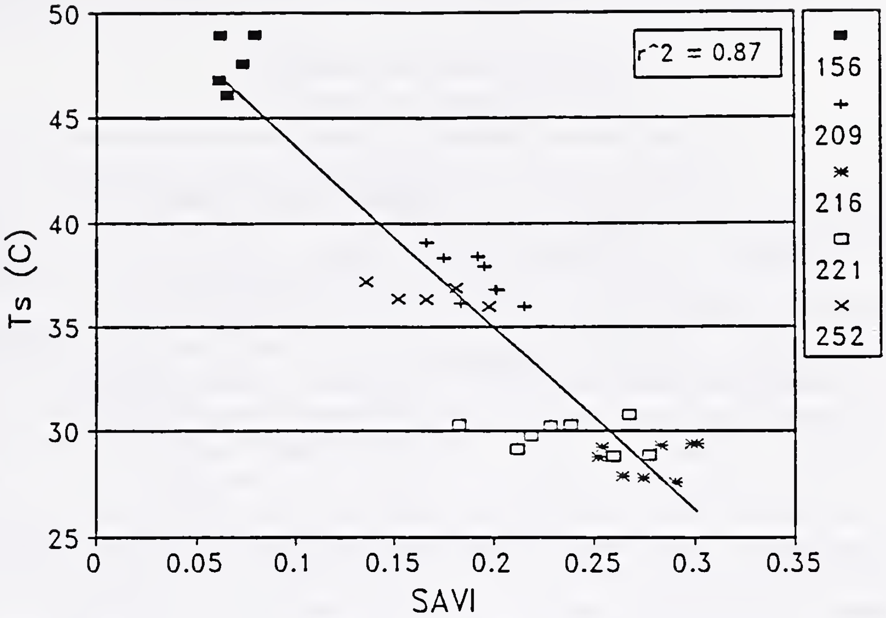

Figure 1. Comparison between surface temperature measurements (T_s) and the soil-adjusted vegetation index (SAVI) for eight METFLUX sites over five measurement dates: days 156, 209, 216, 221 and 252.

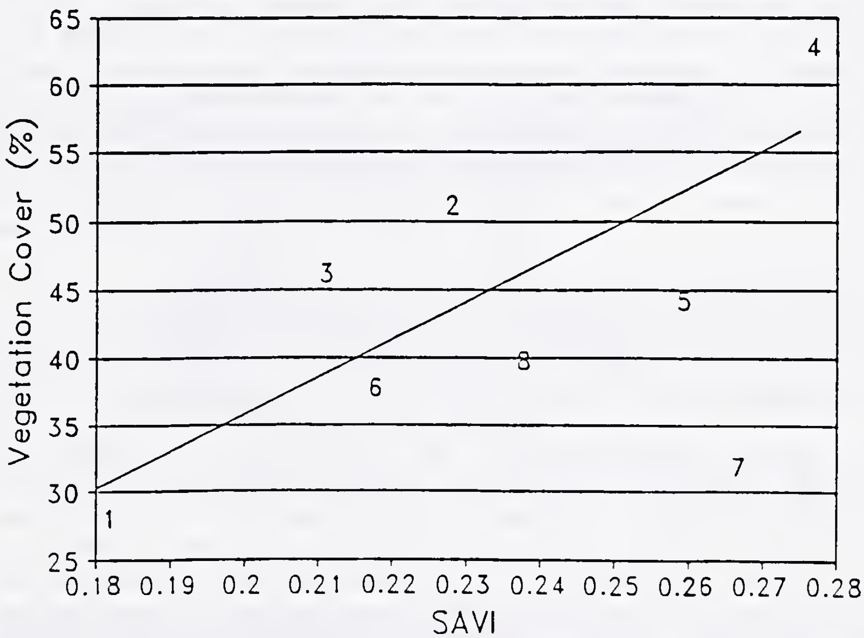

Figure 2. The soil-adjusted vegetation index (SAVI) and percent vegetation cover at all eight METFLUX sites (labeled 1-8) on day of year 221.

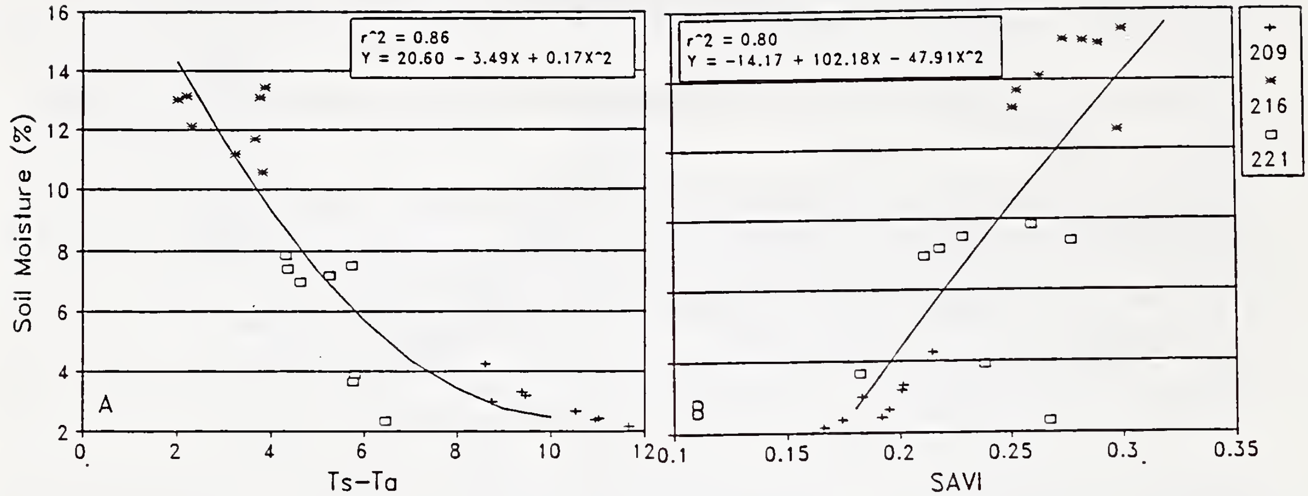

Figure 3. Relations between volumetric soil moisture content and four spectral measurements: A) surface-air temperature (T_s-T_a) and B) soil-adjusted vegetation index (SAVI).

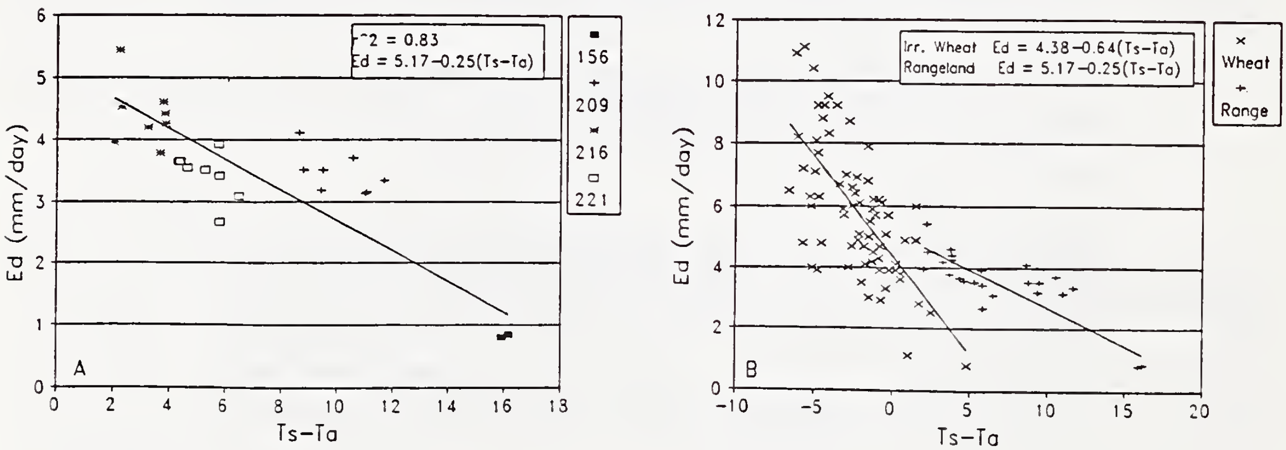

Figure 4. A) Relation between daily surface evaporation rate (mm/day) and surface-air temperatures (T_s-T_a) for the eight METFLUX sites on days 156, 209, 216 and 221. B) Comparison of the rangeland data illustrated in Figure 4A with similar measurements in irrigated wheat published by Jackson et al. (1977).

EVALUATION OF SIMPLIFIED PROCEDURES FOR RETRIEVAL OF LAND SURFACE REFLECTANCE FACTORS FROM SATELLITE SENSOR OUTPUT

M.S. Moran, Physical Scientist and
R.D. Jackson, Research Physicist

PROBLEM: Knowledge of the spectral reflectance of the earth's surface is useful for a wide variety of studies, ranging from detection of plant stress to observation of global surface changes. Regional maps of surface reflectance can be acquired by satellite-based radiometers, but the images must first be corrected for the unwanted influences of the atmosphere. Currently, such corrections can be accomplished by measuring atmospheric optical depth on the day of satellite overpass and using a radiative transfer code (RTC) to compute the relationship between surface reflectance and radiance at the sensor. This procedure has proven to be accurate (Moran et al., 1990), but is too expensive and time consuming to be used on an operational basis. Though several simpler correction procedures have been proposed, none have been verified with accurate ground-based measurements for a variety of atmospheric conditions.

APPROACH: In response to the need for a simple atmospheric correction method and the consequent verification of such a method, an experiment was designed to acquire a data set suitable for testing atmospheric correction procedures under a variety of conditions. Simultaneous spectral data were acquired using satellite-, aircraft-, and ground-based sensors over large, uniform ground targets at Maricopa Agricultural Center (MAC) for a 1-yr period. Atmospheric optical depth was measured during each satellite overpass to characterize atmospheric scattering and absorption.

Surface reflectance factors ($\rho_{g\lambda}$) were derived from satellite-based digital counts (DCs) using three approaches (summarized in Table 1). In the first, on-site optical depth measurements were used as input to an RTC to compute surface reflectance factors based on satellite DC values. This method provided the most accurate results, to be used as a baseline for comparison with results from the simpler approaches. In the second approach, simulated atmospheres were used (in lieu of optical depth measurements) as inputs to an RTC to compute $\rho_{g\lambda}$ values; three reasonable atmospheres were selected: mid-latitude summer, standard U.S. and Rayleigh atmospheres. Third, two "image-based" approaches were tested, in which scene-derived information about the atmosphere was used to retrieve $\rho_{g\lambda}$ values. Both image-based methods derived atmospheric haze information from the spectral response of the darkest object in the scene (e.g., the lower limit of the image histogram). In one approach, the atmospheric transmittance was inferred from the haze value using an RTC (adapted from Ahern et al., 1977) and, in the other (termed the dark object subtraction technique), the need for an RTC was circumvented by assuming that the transmittance was 1.0 (Chavez, 1988).

FINDINGS: Values of surface reflectance derived from Landsat Thematic Mapper (TM) DCs were compared with low-altitude aircraft-based measurements in the visible and near-infrared (NIR) spectral bands. The root mean square error (RMSE) of satellite-derived $\rho_{g\lambda}$ values was computed for each correction method based on reflectance data for 2 ground targets (bare soil and full-cover vegetation), 4 spectral bands, and 7 acquisition dates over a 1-yr period.

The RMSE of reflectance corrected using the Herman-Browning and 5S RTCs with on-site measurements of spectral optical depth was approximately 0.012 reflectance, nearly 70% less than for uncorrected data (Figure 1). The small error associated with reflectance factor retrieval could be attributed in part to error in the satellite calibration, the radiative transfer equations, the ground-based measurements of optical depth and the aircraft-based measurements of surface reflectance and the unknown influence of the atmospheric adjacency effect.

The Lowtran7 RTC based on simulated atmospheres produced variable results depending on the suitability of the atmospheric model (Figure 2). For example, when the Lowtran7 Rayleigh model (L-R) was applied without accounting for atmospheric water vapor absorption, the RMSE of $\rho_{g\lambda}$ estimates was

greater than 0.02. However, when more comprehensive models were chosen (e.g., Standard U.S. or mid-latitude summer models), the Lowtran7 code produced results substantially better than the uncorrected values and comparable to the RMSEs presented in Figure 1. In all cases, the use of RTCs with simulated atmospheres improved the satellite-derived estimates of reflectance.

The dark-object subtraction method (DOS in Figure 3), which accounts only for the additive effect of atmospheric path radiance, resulted in RMSE similar to that for the uncorrected data. This inaccuracy was due largely to the assumption that atmospheric transmittance = 1.0. The hybrid approach (5SD in Figure 3), which combined the image-based nature of DOS with the precision of an RTC, gave results similar to those presented in Figure 1 (RMSE ≈0.015 reflectance). These results reaffirmed the belief that much of the error associated with the DOS technique was due to the disregard for atmospheric water vapor absorption.

Though these results were probably site-specific (characterized by relatively low haze and humidity levels), they illustrate the feasibility of simple atmospheric correction methods and the usefulness of a diverse data set for validation of such techniques.

INTERPRETATION: Overall, these results emphasized the importance of atmospheric correction for retrieval of surface reflectance from satellite-based sensors. As expected, combining RTCs with on-site atmospheric measurements (Figure 1) produced the most accurate estimates of surface reflectance, but RTCs with reasonable estimates of atmospheric conditions (Figures 2 and 3) were surprisingly successful. Thus, it appears that a simple, operational correction method may be feasible to produce regional maps of surface reflectance data for large-scale studies.

FUTURE PLANS: There are plans to apply the most promising atmospheric correction techniques to a larger set of satellite images acquired at MAC with the SPOT High Resolution Visible (HRV) sensor. This analysis will address the atmospheric correction issues associated with oblique sensor viewing geometry. The Arizona Dept. of Water Resources plans to apply the results of this research on an operational basis using SPOT HRV data to monitor and regulate agricultural water use in Arizona.

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Table 1. Summary of atmospheric correction abbreviations used in text and figure caption.

UNC: Uncorrected $\rho_{g\lambda}$ estimates {often termed apparent reflectance}.

Radiative Transfer Codes (RTC) with Measured Input:

HBC: Herman-Browning code (Herman and Browning, 1965), using on-site measurements of optical depth;

5SC: 5S code (Tanré et al., 1985), using on-site measurements of optical depth.

RTC with Simulated Input:

L-M: Lowtran7 (L7) code (Kneizys et al., 1988) using the Mid-Latitude Summer Model default;

L-S: L7 code using the Standard U.S. Atmosphere Model default;

L-R: L7 code using a Rayleigh atmosphere with only gas absorption.

Image-based Correction Methods, With and Without Use of RTC:

DOS: Dark-object subtraction (Chavez, 1988);

5SD: Hybrid method (adapted from Ahern et al., 1977), combining image dark-object information with the 5S RTC.

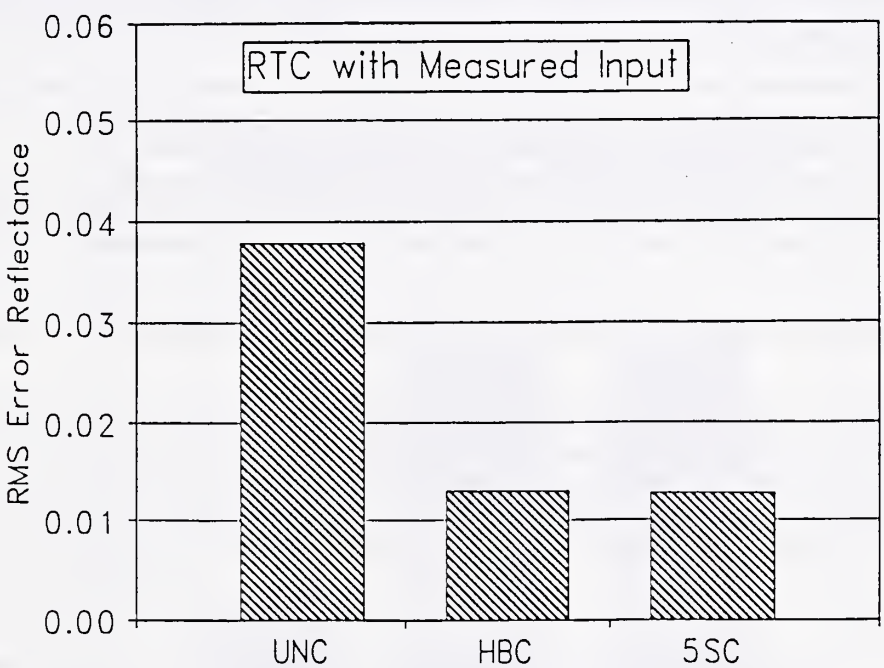

Figure 1. Root mean squared (RMS) error of reflectance factor retrieval using radiative transfer codes (RTC) with on-site measurements of atmospheric optical depth. RMS error was computed for 56 points: 2 targets x 4 bands x 7 dates. X-axis labels are defined in Table 1.

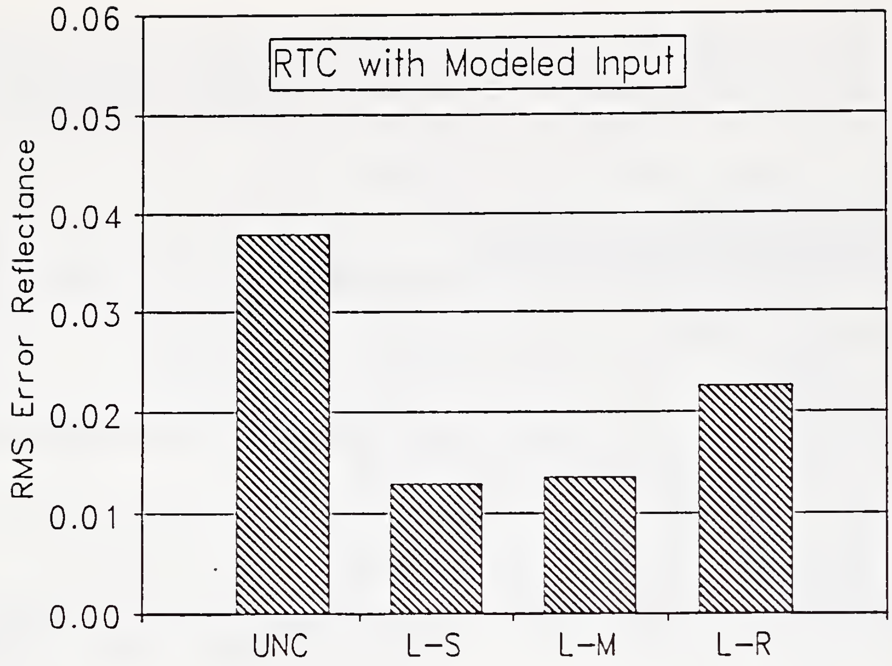

Figure 2. Root mean squared (RMS) error of reflectance factor retrieval using the Lowtran7 radiative transfer code with simulated atmospheres. RMS error was computed for 56 points: 2 targets x 4 bands x 7 dates. X-axis labels are defined in Table 1.

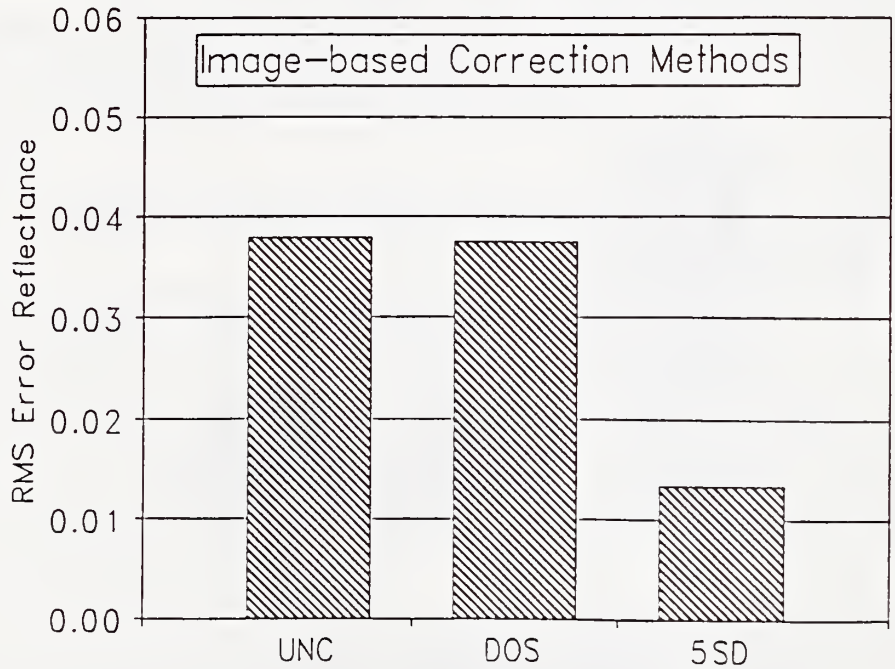

Figure 3. Root mean squared (RMS) error of reflectance factor retrieval using image-based correction methods, with and without use of an RTC. RMS error was computed for 56 points: 2 targets x 4 bands x 7 dates. X-axis labels are defined in Table 1.

INTEGRATION OF OPTICAL AND THERMAL RADIOMETRY WITH DOWN-LOOKING RADAR FOR SURFACE WATER AND ENERGY FLUX EVALUATION: AN INTERNATIONAL COOPERATIVE EXPERIMENT

T.R. Clarke, Physical Scientist and
M.S. Moran, Physical Scientist

PROBLEM: The use of airborne and satellite-based radar platforms for detecting moisture in the top few centimeters of the soil profile is a relatively new tool for studying water dynamics in agricultural and rangeland areas. The emerging technology will hopefully obviate the herculean task of manually sampling soil moisture over large areas, and facilitate study of the hydrological cycle over local, regional, and global scales.

One hurdle which must be overcome before radar detection can be used is determining and hopefully compensating for the effects of overlying vegetation on the radar return. Measurements of surface reflectance and temperature acquired simultaneously with the radar data may provide an effective means of estimating the amount of vegetation covering the surface. The integration of optical and thermal radiometry with radar could improve the estimates of regional surface water and energy flux.

APPROACH: An international, multi-agency experiment was conducted at the Orgeval Watershed 50 km east of Paris, France, in June and July of this year. Radar equipped platforms included a NASA DC-8 with Synthetic Aperture Radar (SAR) and a CNET-CRPE Allouette helicopter with a down-looking flat-array radar. High- and medium-altitude optical data were collected by a NASA ER-2 equipped with the Thematic Mapper Simulator (TMS) and Airborne Visible and Infrared Imaging Scanner (AVIRIS) sensors, and a French aircraft with a POLDER side-looking multi-spectral radiometer. A Landsat Thematic Mapper (TM) image was also acquired.

Ground and low-altitude multi-spectral measurements were made by a NASA-funded American team consisting of two USWCL scientists and two graduate students from the University of Arizona Department of Hydrology and Water Resources. Optical and thermal measurements were made from the Allouette helicopter as it flew along radar transects over wheat and corn fields, while yoke-based radiometers measured the same targets in greater detail. French researchers collected soil moisture and plant samples, Bowen ratio energy flux measurements, and assisted in ground-based reflectance and surface temperature data collection. Intensive measurements were carried out in two 10-day sessions in mid-June and late July.

FINDINGS: Data reduction and analysis is still in a preliminary stage and it is too early to present any results.

FUTURE PLANS: Analysis of data will continue, including attempts to correlate spectral vegetation indices with surface and plant characteristics and to estimate surface evaporation using surface reflectance and temperature measurements acquired during cloudy conditions. Comparisons of optical and thermal data with Bowen ratio and radar results will be made as these data become available. A similar campaign, but on a much larger scale, has been scheduled for Niger, West Africa, in late Summer 1992, with many of the same participants.

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AIRCRAFT-BASED BIDIRECTIONAL REFLECTANCE OF AGRICULTURAL TARGETS

T.R. Clarke, Physical Scientist;
M.S. Moran, Physical Scientist; and
R.D. Jackson, Research Physicist

PROBLEM: Because light is not reflected evenly in all directions from agricultural surfaces, the data collected by satellite and airborne sensors require a means of compensating for the various sun angles and sensor view angles encountered in normal practice. For example, nadir satellite images taken at the same time of day over a growing season will be illuminated at different sun angles as the season progresses, producing an apparent change in reflectance not caused by a change in the surface itself. Likewise, two satellite images taken at different look angles may give very different results for identical targets. Real changes in target reflectances can thus be masked by the apparent changes caused by different look angles and solar zenith angles.

A major barrier to resolving this problem has been the lack of reliable data taken over large areas at discrete sensor look angles and solar zenith angles. Previous efforts have depended upon stationary devices viewing very small areas, which is effective for uniform surfaces but not for row crops or rangeland.

APPROACH: Radiometers sensitive to radiation in the blue (TM-1), green (SPOT HRV-1), red (HRV-2), near infrared (HRV-3), and thermal infrared (8 - 14 microns) spectral bands and having 15 degree fields of view were mounted on a pointable platform extending from the door of a light aircraft. The radiometers could be pointed straight down (nadir) and at angles of 10, 20, 30, and 40 degrees off nadir, along the aircraft's direction of flight. By flying the aircraft directly toward the sun and away from the sun at each look angle setting, a total of 9 look angles of the same target transects were achieved in a short time.

Two transects were flown over The University of Arizona Maricopa Agricultural Center, covering 3 bare soil fields, 2 cotton fields, and a pecan orchard. The transects were repeated several times from early morning to near solar noon, providing a variety of solar zenith angles. All measurements were made in a thirty hour time period to minimize actual changes in target reflectances.

FINDINGS: Preliminary data analysis has been limited to the red and near infrared bandwidths, and for the bare soil and cotton targets of Field 31 only. The data were analyzed as a function of bidirectional angle, which is the sum of the look angle and solar zenith angle. Look angle was considered positive if the sensors' view was toward the sun, and negative if pointed away from the sun (see Figure 1). Sensors pointing straight down (nadir view) had a look angle of 0 degrees, and hence a bidirectional angle equal to the solar zenith angle.

In the red band (Fig. 2 and 3), both surfaces demonstrated a similar curvilinear response to changing bidirectional angle, with a maximum reflectance at angles near 0 degrees (sun directly behind the sensor) and a minimum near 90 degrees (sun rays perpendicular to look angle).

In the near infrared band, the bare soil response to changing bidirectional angle (Fig. 4) is similar to that of the red band, while the cotton target (Fig. 5) shows distinctly different bidirectional curves at different solar zenith angles.

INTERPRETATION: It appears that the non-lambertian qualities of agricultural surfaces in the red spectral band can be adequately described based on bidirectional angle (look angle + solar zenith angle). Because of the relatively wide field of view of the radiometers used, the precise behavior of the reflectance maxima as the bidirectional angle approached 0 degrees could not be determined.

The response in the near infrared appears more complex, probably due to the partial transmissivity of leaves to that spectral band, resulting in a greater complexity of reflectance paths. In Figures 6 and 7, the relative sensitivity of the surface to a 20 degree change in solar zenith angle (vertical distance AB) and a 20 degree change in look angle (vertical distance BC) for bare soil and near full canopy cotton can be

observed. While the bare soil shows equal sensitivity to the two components of the bidirectional angle (Fig. 6), the cotton shows little sensitivity to solar zenith angle relative to look angle in the -20 to +20 degree look angle range (Fig. 7). It would seem that the sensitivity of the near infrared response to changing solar zenith angle is inversely proportional to the amount of vegetation present.

FUTURE PLANS: In order to experimentally confirm the reflectance behavior as the bidirectional angle approaches 0 degrees, further measurements must be made using 1 degree field of view optics. Measurements should also be made over intermediate canopy densities. We hope to accomplish these goals in 1992.

COOPERATORS: J. Qi, Department of Soil and Water Resources, and D. S. Ammon, Department of Agricultural and Biosystems Engineering, The University of Arizona, Tucson, AZ

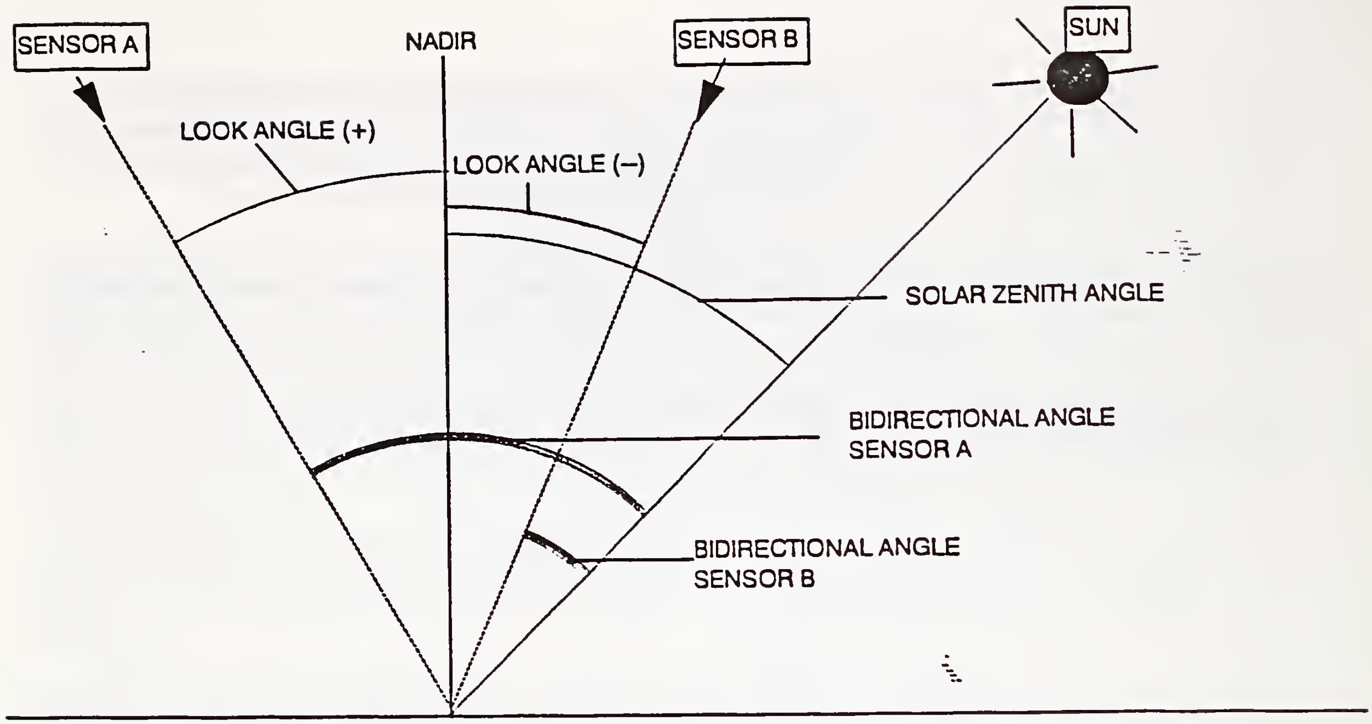

Fig. 1 Geometry of the sun-surface-sensor bidirectional angle along the solar azimuth, or principle plane.

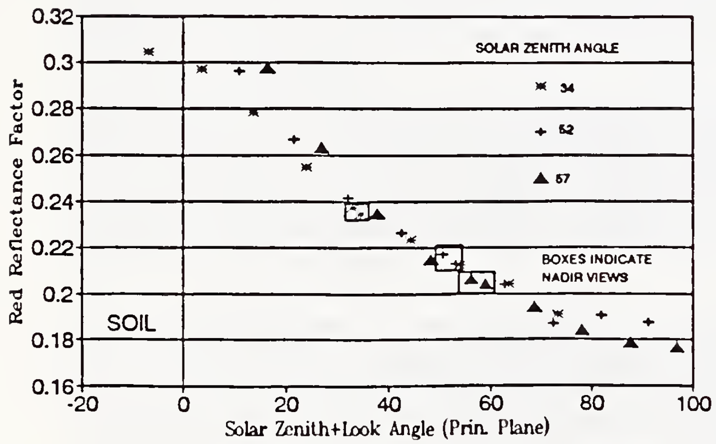

Fig. 2 Red reflectance over soil as a function of bi-directional angle at 3 solar zenith angles.

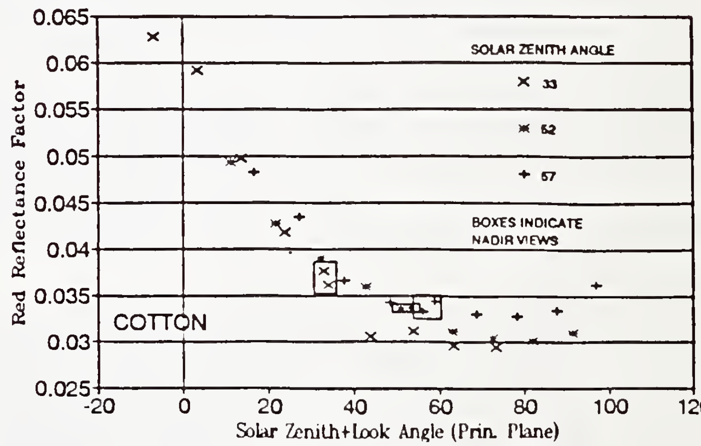

Fig. 3 Red reflectance over cotton as a function of bi-directional angle at 3 solar zenith angles.

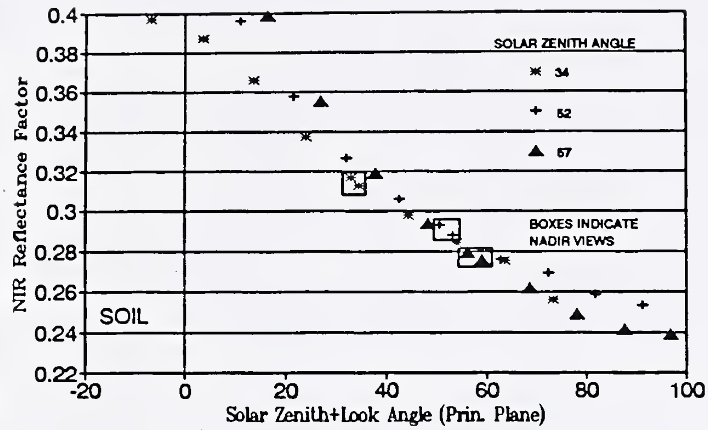

Fig. 4 NIR reflectance over soil as a function of bi-directional angle at 3 solar zenith angles.

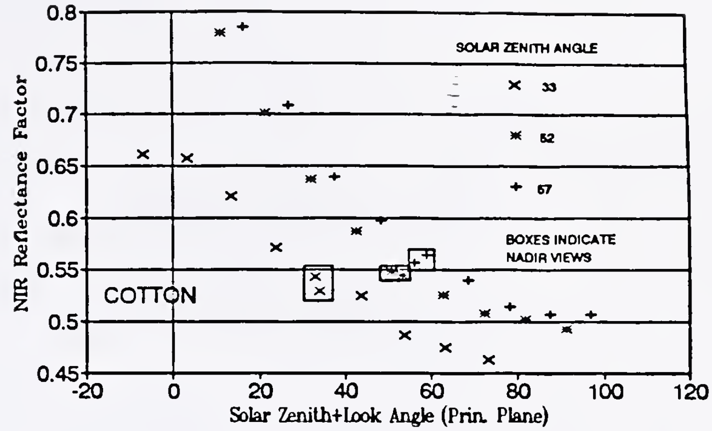

Fig. 5 NIR reflectance over cotton as a function of bi-directional angle at 3 solar zenith angles.

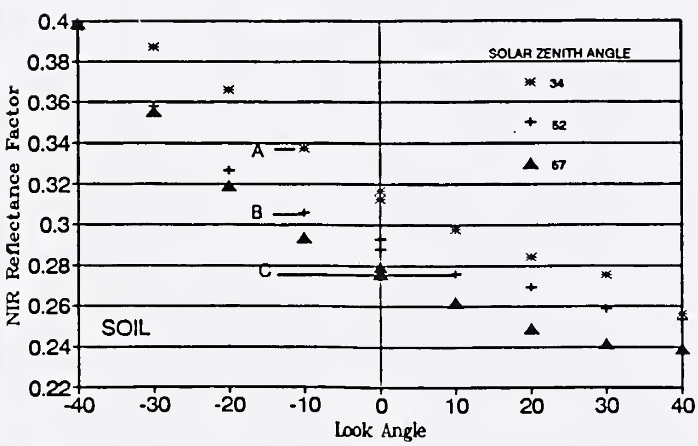

Fig. 6 Comparison of component sensitivities (solar zenith vs. look angle) of NIR reflectance over soil.

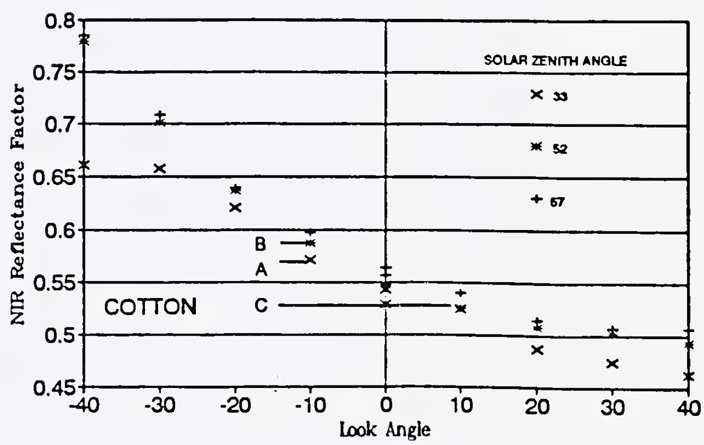

Fig. 7 Comparison of component sensitivities (solar zenith vs. look angle) of NIR reflectance over cotton.

GERMPLASM IMPROVEMENT AND CULTURAL DEVELOPMENT OF NEW INDUSTRIAL CROPS

GUAYULE BREEDING

D. A. Dierig, Research Geneticist; A. E. Thompson, Research Geneticist; and
F. S. Nakayama, Research Chemist

PROBLEM: Guayule is a rubber producing plant of the southwest desert with good potential for commercialization. The billion dollars in imports the United States spends annually on natural rubber warrants research on breeding high yielding cultivars for domestication. Since the guayule breeding program began at the U.S. Water Conservation Laboratory in 1986, yields have been increased over standard lines. Further increases are necessary to economically compete with the tropical Hevea rubber tree, which is the present source of imported rubber. Guayule breeding is complicated by facultative apomixis in the polyploid population, self-incompatibility in the sexual reproducing diploids, along with other biological anomalies. The goal of the breeding program is to produce high rubber yielding cultivars by generating variability for desirable characteristics that contribute to yield.

APPROACH:

1. Greenhouse cross pollinations include sexual diploids hybridized with polyploid apomictics. Parents in these crosses have been selected for improved rubber content, regeneration capability, and vigorous growth. The purpose is to exploit variability of apomictic plants by forcing new recombinations using the apomictics as a male parent. Crosses are being generated to examine the mode of inheritance of a six ray florets per capitulum. Five ray florets per capitulum is normal. Only one other phenotypic marker has been reported in guayule.
2. A diploid population has been screened for rubber content and the progeny of the most promising plants have been field planted to create a new, open pollinated, population. This population will be evaluated and superior plants selected to create the next generation of a recurrent selection population.
3. Increasing rubber production is being approached by examining the feasibility of harvesting new higher yielding selections at an earlier age. Three new breeding lines were planted at three different spacings. Sampling will be completed each year to determine when it is practical to harvest in comparison to the conventional practice of a three year harvest.
4. A regional uniform variety trial was established at The University of Arizona Maricopa Agricultural Center, Maricopa, Arizona, in spring of 1990. The same breeding lines were also planted at four other western United States locations. The breeding lines for this trial included two new lines from California, four new lines from this breeding program, two lines from the previous variety trial, and two standard varieties used as checks along with observational lines. The first harvest of these plants will take place this spring when plants are two-years-old.
5. New breeding lines from single plant selections are continued to be evaluated. Three separate yield trials are planted at Maricopa. The breeding lines from one of these trials is also in a cooperative planting in Riverside, California, and in Fort Stockton, Texas. A total of seventy breeding lines from these three replicated yield trials are being evaluated for improved rubber content and yield, plant vigor, and regeneration ability.
6. Plants from seed selected for early germination and seedling vigor have been planted. Seed is being harvested from these plants and selection is continuing for this trait. The resulting lines will be incorporated into a direct seeding trial to measure the success of this selection.

FINDINGS:

1. Hybrids from greenhouse crosses have been field planted this past spring. Selections from single plants will be made as plants mature and can be evaluated. The F_1 generation indicates that the six flower characteristic is under genetic control and is a dominant trait. Since diploids are self-incompatible, test crosses are being made to determine the number of genes that control this trait.
2. Ten new high yielding lines have been identified from the diploid population. These top lines may now be planted together to form a new open pollinated population and further select from here.

3. Plant spacings of new breeding lines for early harvest have not yet been evaluated. The first sampling will take place this spring when plants are 1-year-old.

4. Plants of the regional uniform variety trial will be sampled at all locations this coming spring. These plants will be two-years-old at this time and will be sampled again the third year.

5. Two-thirds of these yield trials have been sampled at one, two, or three years. The breeding lines which performed best at this location have been identified and have acceptable yields. These lines are again being grown to further select and eliminated offtypes. Harvests have taken place at the other two locations and data are being analyzed.

6. Significant differences occurred in the rates of germination between 50 lines grown under the same environmental conditions. Within each line the earliest germinating plants were planted and continued selection for this trait is being carried out.

INTERPRETATION: Variability is extremely important for success in any plant breeding program. Guayule is limited in genetic variation because of the apomictic nature. Significant progress is being achieved in increasing rubber production through various methods of selection and intraspecific hybridization. Since guayule is a perennial, the breeding program requires a long term plan. The appropriate crosses and selection process are taking place at successive generations.

FUTURE PLANS: A continuation of the recurrent selection program will be emphasized. The diploids in this program will also be used as female parents in crosses with high yielding apomictic selection. This will be done both in the greenhouse and in the field in the spring of 1992. Progeny from both approaches can then be compared. Other yield trials now in progress will continue to be harvested and evaluated with further selection within populations. New germplasm will be collected and evaluated from Fort Stockton, Texas this year. Close cooperation will be taking place at this site due to the large amount of germplasm already established there.

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Dr. M.A. Foster, Texas A&M Experiment Station, Ft. Stockton, TX
Dr. A. Estilai, University of California, Botany Department, Riverside, CA

GERMPLASM IMPROVEMENT AND COMMERCIALIZATION OF LESQUERELLA

A.E. Thompson, Research Geneticist; D.A. Dierig, Research Geneticist;
F.S. Nakayama, Research Chemist; and D.J. Hunsaker, Agricultural Engineer

PROBLEM: The development of lesquerella as a new industrial oilseed would significantly contribute to the improvement of United States agriculture and the general economy of the country. The United States is completely dependent upon imported castor oil, a strategic material, for its total supply of hydroxy fatty acids. Annual imports are currently around 40-50 metric tons, with a value of about $40 million. Because of the unique chemical structure of lesquerolic acid in the seed oil, which is slightly different from that of ricinoleic acid in castor oil, it is seen as more than just a partial replacement for castor oil. Initial genetic and agronomic research conducted at this location has given encouragement to a full scale commercialization effort. The objectives of this research is to evaluate and develop improved germplasm, to develop appropriate cultural and water management practices, and to assess the potential for full commercialization.

APPROACH:

1. Collect, evaluate and enhance lesquerella germplasm for increased seed, seed oil, and hydroxy fatty acid yields; increased seed size and plant height; earlier flowering and seed set; and other improved plant growth characteristics by using appropriate breeding, genetic, and cytogenetic techniques.
2. Make appropriate genetic crosses, select, test, and develop high yielding cultivars or hybrids capable of full commercialization.
3. Develop and evaluate appropriate cultural and management systems including planting rates and methods; water use, weed and pest management; seed production and harvesting methods.
4. Work cooperatively with private industry and other public research entities to increase basic and applied research, and to increase lesquerella seed for pilot plant oil extractions and evaluations; oil and meal utilization; and new product development for full commercialization.

FINDINGS: Field plot research during the 1990-91 growing season included replicated experiments on water use; a comparison of planting methods (level basin vs. 40" raised beds) at 3 seeding rates (4,6 & 8 lbs/ac); and yield evaluation of 6 selections and their topcrossed progenies. A large 16 acre field was also planted at The University of Arizona Maricopa Agricultural Center in cooperation with the Jojoba Growers & Processors, Inc. and Agrigenetics/Lubrizol companies to provide seed for pilot plant extractions and continued utilization research. The large scale water use study was located on one-half of the 16 acre field. In general, plant stands and growing conditions were excellent. However, the yields in general were lower than expected. To date, not all of the yield data are analyzed and the chemical evaluation for oil and fatty acid content at the National Center for Agricultural Utilization Research (NCAUR), Peoria is not complete. Several significant problems have been noted. Control of early and late spring weeds was not effective. Heavy infestation of Russian thistle, caused difficulties in harvesting resulting in loss of seed, and excessive trash and moisture in the harvested seed. This problem was especially serious in the water management plots. At times, over 30% of the seed was not harvested due to this problem. No significant differences in seed yields were measured in the replicated test that compared yield on 40" raised beds with that on level basins. The 6#/acre seeding rate appeared to be optimal in this experiment. Overall it was observed, especially in the 16 acre field, that seed set on the plants was lower than in previous years. The plants continued to flower indeterminately, and maturity and harvesting was delayed.

INTERPRETATION: Overall, the research results are very positive. The Lesquerella Commercialization Task Force Report, which is currently in press, provides a favorable assessment of lesquerella's future. Increased utilization of lesquerella oil for new industrial applications is clearly visualized by several private companies, which are showing considerable interest and providing financial resources for cooperative research and development. A primary objective of the increased industry funding of this research is to

improve cultural and water management practices to accelerate full commercialization. Research on weed control and development of effective protocols for effective herbicides that can be approved by IR-4 and EPA are needed. Slight modifications to the combine harvester's header are needed to improve pickup of plants from irrigation furrows on the 40" raised beds. Modifications in planting methods should also improve harvesting efficiency, which when compared to hand harvested plots in previous years on level fields has been as high as 85% with a standard combine. Continued research on water use efficiency and timing of water application is needed. Selection of plants, which are autofertile and will set seed without pollinating insect mediated cross pollination, and have higher seed oil and fatty acid content is needed. The germplasm evaluation and enhancement, and the breeding and selection program is seriously constrained due to the lack of sufficient funds to support qualified technical assistance for timely oil and fatty acid analysis.

FUTURE PLANS: Research plantings made in October at MAC and in the lysimeter field at the USWCL, Phoenix, will be harvested in May or June, 1992. These plantings were made in cooperation with Mr. John Nelson of The University of Arizona under a new specific cooperative agreement. They include replicated experiments on dates of planting, planting methods, weed control, and a new cycle of selection and breeding. Replicated plots on the large 20 acre field, partially financed by industry, are comparing planting methods including level basin, 40," 30," and 20" raised beds. About 90 additional acres of research plots and pilot production fields have also been planted in cooperation with industry in California, Arizona, Texas, Oklahoma, Colorado, Oregon, and Virginia. Cooperative research with the USDA-ARS Bee Laboratory in Tucson is being planned to determine pollination requirements and floral biology of lesquerella. If sufficient funds are available, facilities will be developed to conduct oil and fatty acid analysis on the large number of samples generated by the breeding and genetics, and the cultural and water management research.

COOPERATORS:

J.H. Brown, K. Dwyer, J.D. Arquette, Jojoba Growers & Processors, Inc.
Apache Junction, AZ
K.A. Walker, B. Phipps, A. Hill, Agrigenetics Company,
Eastlake, OH, Goodyear, AZ, and Woodland, CA
J.M. Nelson, R.L. Roth, J.C. Wade, P.N. Wilson, Univ. Arizona,
Maricopa Agricultural Center and Tucson, AZ
E.H. Erickson, S.L. Buchmann, A.N. Mahmood, USDA-ARS, Tucson, AZ
M.A. Foster and J. Moore, Texas A&M, Fort Stockton and Pecos, TX
S.J. Knapp and R.J. Roseberg, Oregon State Univ.
Corvallis and Medford, OR
D.L. Johnson, Colorado State Univ. Fort Collins, CO
H.L. Bhardwaj, Virginia State Univ. Petersburg, VA
R. Kleiman and K.D. Carlson, USDA-ARS-NCAUR, Peoria, IL
J.C. Roetheli and D.A. Kugler, USDA-CSRS-SPPS Office of Agricultural Materials,
Washington, DC
L.K. Glaser, USDA-ERS, Washington, DC

GERMPLASM IMPROVEMENT OF VERNONIA

A.E. Thompson, Research Geneticist; D.A. Dierig, Research Geneticist; and
F.S. Nakayama, Research Chemist

PROBLEM: Vernonia galamensis produces seed oil with high quantities of epoxy fatty acids. These are useful in the reformulation of oil based (alkyd-resin) paints to reduce emissions of volatile organic compounds (VOC) that significantly contribute to air pollution. Other potential markets include PVC plastics, other polymer blends, baked coatings, and cosmetic applications. No other germplasm exists, which contains naturally occuring epoxy oils that have such good potential for commercialization. Until recently, all available Vernonia galamensis germplasm, which comes from Africa, required short day photoinduction cycles to produce flowering and subsequent seed production. One accession, A399 (V029), of the subspecies galamensis var. petitiana was found to be day neutral and will flower any time of the year in Arizona and other locations in the U.S. However, it has some undesirable plant characteristics such as indeterminate flowering and excessive loss of seed at maturity. The objective of this research is to develop high yielding germplasm and cultivars that will be adapted to production in the U.S.

APPROACH:

1. Evaluate and enhance germplasm of vernonia for high seed oil yield and fatty acid content; day neutral flowering; autofertility; vigorous seed germination, emergence, and seedling growth; and good mature seed retention using appropriate breeding, genetic, and cytogenetic techniques.
2. Make appropriate genetic crosses, select, test, and develop high yielding cultivars capable of full commercialization.
3. Develop and evaluate appropriate cultural and water management systems.
4. Work cooperatively with private industry and other public research entities to expedite full commercialization.

FINDINGS: The USDA-ARS-USWCL Vernonia Working Germplasm Collection of 38 accessions were evaluated in the greenhouse and field. Data were taken in the greenhouse on the number of seeds set after controlled self pollinations. Considerable variation in the amount of autofertility was measured both within and among accessions. Crosses were made, utilizing A399 (V029, subspecies galamensis var. petitiana), which is autosterile, as the female parent with A382 (V001, subspecies galamensis var. ethiopica); A388 and A389 (V003 & V004, subspecies galamensis var. galamensis); and A437 (V013, an accession from Tanzania that has not been classified as to subspecies and variety). A large population of putative F1 plants are being grown and cytologically verified in the greenhouse during the fall and winter of 1991-1992. Autofertility of F1 plants is being evaluated by controlled self pollinations. F2 seed is being produced for field evaluation and selection of desirable recombinations of agronomic characters essential for production in the U.S. Selected backcrosses are being made of the F1 to the original parents. Analysis of oil and fatty acid contents of all available germplasm is currently in progress at the NCAUR, Peoria.
A replicated yield test was conducted at The University of Arizona Maricopa Agricultural Center using the A399 petitiana material. Four planting dates (2/13, 2/27, 3/13, & 3/27/91) were made by direct seeding with four planting rates (1.25, 2.5, 5.0, & 10.0 lb./ac). A split-plot treatment of topping (removal of the terminal buds when plants were about 6" tall) vs. no topping was superimposed. Topping, which has been used successfully with the Ethiopian germplasm in Zimbabwe, was used in an attempt to synchronize flowering and seed set. Good plant stands were obtained at all planting dates and at all planting rates except the lowest. Difficulties were experienced in harvesting due to uneven maturation of flowers and seeds, and excessive seed loss due to shattering. Yield data are not yet available, but preliminary information indicates that topping reduced seed yield.

INTERPRETATION: None of the existing germplasm is adapted for culture in the U.S. Before production is feasible, improved germplasm and cultivars will have to be developed that will flower under

the long-day growing conditions. Additionally, an array of other characteristics will have to be favorably combined to make vernonia a commercial success. Fortunately, most of the desired characteristics have been found in the various accessions that are currently available in our germplasm collection. Since many of these accessions of vernonia came from arid regions of Africa, there is a good probability that adapted cultivars can be developed that will have good water use efficiency. The crosses we have made among these species should provide the raw material for selection. Once new selections are made, crop and water management research will be initiated. The breeding and selection program is seriously constrained by not having adequate technical assistance for conducting oil and fatty acid analysis at the USWCL in Phoenix.

FUTURE PLANS: F2 seed of the four intervarietal vernonia crosses, currently being generated in the greenhouse, will be space planted at MAC for evaluation and selection within the segregating populations. Favorable recombinations of agronomic characters such as day neutral flowering response; good seed germination, seedling emergence and vigor; autofertility and good seed set; good mature seed retention; and high seed oil and vernolic acid content will be sought. Seed from a limited number of selections will be sent to NCAUR, Peoria for oil and fatty acid analysis. Aliquots of the F2 seed will be distributed to cooperating scientists in Texas, Oregon, Colorado, Iowa, and Virginia for evaluation and selection under their environmental conditions. If adequate funds permit hiring a qualified technician, equipment will be set up to conduct oil and fatty acid analysis to screen segregating progenies. A seed increase planting of A399 in early April at MAC is planned, which will allow for experimentation on harvesting methods and other cultural practices.

COOPERATORS:

R. Kleiman and K.D. Carlson, USDA-ARS-NCAUR, Peoria, IL
W.W. Roath, USDA-ARS-NCRPIS, Ames, IA
M.A. Foster, Texas A&M Expt. Station, Fort Stockton, TX
S.J. Knapp and R.J. Roseberg, Oregon State Univ.,
Corvallis and Medford, OR
D.L. Johnson, Colorado State Univ. Fort Collins, CO
A.I. Mohamed, M.E. Kraemer, M. Rangappa, and H.L. Bhardwaj,
Virginia State Univ. Petersburg, VA

**CULTURAL MANAGEMENT OF LESQUERELLA:
WATER & STRESS MANAGEMENT**

F.S. Nakayama, Research Chemist; D.J. Hunsaker, Agricultural Engineer;
D.A. Dierig, Geneticist; and A.E. Thompson, Geneticist

PROBLEM: The cultural management of new crops such as lesquerella has not been fully explored. Since its cultivation is more suitable to its native arid southwest habitat, information on its water requirement and irrigation management for this region is needed. The objective of this research is to determine the water use and water stress behavior of lesquerella under various irrigation regimes.

APPROACH:

1. Determine the water requirement, water use, and seed yield of lesquerella under various irrigation regimes.
2. Develop crop water stress index criteria for lesquerella for use in predicting yields and scheduling irrigation.

FINDINGS: Water use and water requirements of lesquerella were determined for three irrigation treatments when 40% (wet), 60% (medium), and 75% (dry) of the soil water in the 180 cm depth was depleted. The number of irrigations per season turned out to be 6, 4 and 2, for the wet, medium and dry, respectively, in 1991. The seed yield - water use data for the 1991, 1989, and 1988 harvest years are compared in Table 1.

Table 1. Water Use and Seed Yields of Lesquerella

(1991)			(1989)			(1988)		
No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)	No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)	No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)
2	485	1035	4	450	1235	3	400	660
4	620	1110	<u>6</u>	<u>630</u>	<u>1280</u>	4	550	1060
<u>6</u>	<u>635</u>	<u>1125</u>	8	565	1130	5	630	1090
-	-	-	10	625	1120	<u>6</u>	<u>625</u>	<u>1420</u>

The crop water stress indexing (CWSI) technique based on remote sensed infrared measurements was applied to the irrigated lesquerella crop. Baselines were developed and CWSI monitored through the later part of the crop growing cycle.

INTERPRETATION: The water use and seed yield of lesquerella for the harvest year 1991 were similar to that of the preceding 1988 and 1989 years. Seed yields of approximately 1000 kg/ha were obtained with about 500 mm water use per season. The yield in the 1991 "dry" treatment is higher than the preceding years, however, and an extra water application may have been made, but not recorded. CWSI measurements (Fig. 1) indicate the possibility of an irrigation of the dry plot at the Julian date of approximately 120. There is a distinct lowering of the CWSI for the dry plot similar to the irrigated wet and medium water treatments even though the dry plot was not supposed to be irrigated at this time.

Thus, if water was applied, the water use for the dry treatment would have been more like 600 mm instead of the 485 mm value.

The CWSI equation of CWSI = 2.91 - 1.78 VPD was obtained for the lesquerella crop and is similar to other crops obtained at this laboratory. Questions were raised in developing this relation because lesquerella, unlike other traditional crops, had a large amount of flowers at an early stage of development, so that the canopy temperature measurements included both the leaves and flowers. Another problem with this crop is that full canopy cover is not attained until the last two months of the seven month period from planting to harvest. Thus, crop water stress indexing is not applicable at the early growth cycle for irrigation scheduling. However, the latter two month period could be the most critical for seed formation and maturation so that some flexibility exists for timing water application.

FUTURE PLANS: Plans to continue the existing study and expand the scope of the research include: (1) establish field experiments covering a wider range of water treatment and water stress regimes, (2) determine water stress status in the lesquerella at a younger growth stage with pressure bomb and/or psychometric measurements when the CWSI procedure is not suitable, (3) determine the morphology and possible stomatic activity of the flowers, (4) determine the photosynthesis of the field crop at the various water treatment levels, and (5) establish a specific cooperative agreement with MAC personnel so that more intensive field measurements can be made.

COOPERATORS: J. Nelson, Agronomist, The University of Arizona, Maricopa Agricultural Center.

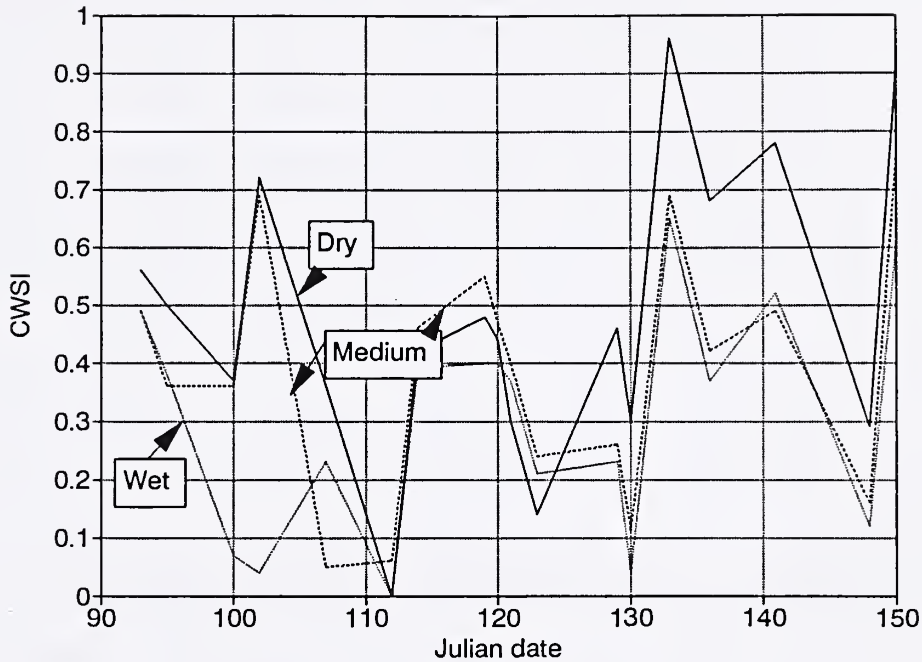

Figure 1. Crop water stress index of lesquerella for the various irrigation treatments.

LABORATORY SUPPORT STAFF

ELECTRONICS ENGINEERING LABORATORY

D. E. Pettit, Electronic Engineer

The Electronics Engineering Laboratory is staffed by an Electronics Engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U. S. Water Conservation Laboratory research projects. Other responsibilities include repair and modification of electronic equipment and advising staff scientists and engineers in the selection, purchase, and upgrade of sophisticated equipment.

During 1991, projects included modernizing and renovating the electronic workbench, test equipment, and computer-aided design (CAD) station; updating reference materials; and restocking of parts and tools. Tool storage units were added to each of the workbench stations. The latest upgrades in hand-held digital voltmeters and universal chip programmers were obtained. Programmable Logic Design and Logical Device Modeling capabilities were added to the three existing in-house CAD packages (Schematic Design, Printed Circuit Board Design, and Digital Simulation Analysis). This software provides the Laboratory with advanced capabilities for the design of electronic projects. An automated Etchant Tank was purchased that enhances the etching process of printed circuit boards in small production runs (under fifty pieces) and also provides the capability of making small fine-line printed circuit boards.

Direct research program support included development of a standard RS-232 electronic interface between a Minolta hand-held chlorophyll meter (Model SPAD-502) and a Polycorder portable data logger (see Rice *et al.*, "Nitrogen Fertilizer and Water Transport Under 100% Irrigation Efficiency," p. 30; and Adamsen *et al.*, "Nitrogen Budgets of Irrigated Crops Using Nitrogen-15 Under High Efficiency Irrigation," p. 32 in this report).

Another design project provided a variable, cyclic timing module that alternated gasses between reference and sample cells of a CO_2 gas analyzer and signaled a data logger that such a switch occurred (see Garcia, Kimball and Wall, "The Influence of CO_2 Enrichment on Canopy Photosynthesis of Cotton," p. 50 in the report).

All of the CO_2 analyzers were repaired and tested after lightning strikes to commercial AC power lines at the Maricopa Agricultural Center caused extensive damage to electronic devices used in the Free Air Carbon Dioxide Enrichment experiment, a cooperative project sponsored by Brookhaven National Laboratory and ARS (see Kimball *et al.*, "Effects of Free-Air CO_2 Enrichment (FACE) on Growth and Yield of Cotton," p. 36 in this report).

Repairs and improvements were made to the electro-mechanical system for managing CO_2 concentrations in open top cotton and tree chambers used in several Laboratory research programs over the past 8 years. This included rebuilding the AC control section, modifications to electrical hardware, realignment of the Anarad CO_2 gas analyzer, and changes to the software controlling the CO_2 valves (see Idso and Kimball, "CO_2 Enrichment of Trees," p. 58 in this report).

Overall Laboratory support included installing a 30-amp electrical service to a new uninterruptable power supply (UPS) for the power management system. The UPS provides AC power to the host computer system of the Local Area Network (LAN) during commercial power outages.

COMPUTER FACILITY

T.A. Mills, Computer Programmer Analyst

The computer facility is staffed by one full-time Computer Programmer Analyst (Terry Mills) and one Computer Assistant (Harold Mastin). Support is provided to all laboratory computer equipment and applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining most computer systems located at the Laboratory. Systems include a Hewlett-Packard HP 1000, a DEC MicroVax II, over 50 personal computers (PCs), including a PC-based network server. A standard Ethernet backbone connects five laboratory buildings and trailers. Two 10Base-T hubs are connected to the backbone. The network supports Novell Netware 386 3.11 and Digital's DECNET and PCSA.

During 1991, the major focus was finding and installing a more economical alternative to the minicomputers and the network services they provided. While Mr. Mills' time was directed toward the new system, it became necessary for Mr. Mastin to become more involved with the laboratories PCs. As a result, Mr. Mastin handled most of the PC problems, including training, updating, and troubleshooting both hardware and software.

The net PC-based network selected was provided by Novell. The file server is currently an AST 486/25 TE computer with 16 megabytes of memory, 1.2 gigabytes of hard disk storage, and a 1-gigabyte erasable optical drive. Twenty desktop PCs and one laptop PC are connected through the 10Base-T hubs. Four HP Laserjet IIs, one HP Laserjet III desktop, one HP Laserjet IIIsi, and one 600 line/minute line printer are available across the network.

During Fiscal 1992, a part-time person will be employed to help transfer programs and data from the two minicomputers onto an erasable optical disk. Network user training will be necessary for users to take full advantage of the resources that are being made available. The PC network will continue to be expanded to include most of the remaining PCs. Electronic mail and a communication server are expected enhancements for FY92.

LIBRARY AND PUBLICATIONS

L. S. Seay, Publications Clerk

Library and publications functions, performed by one Publications Clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff,[1] as well as for holdings of professional journals and other incoming media. Support includes performance of searches for requested publications and materials for the Staff. Library holdings include approximately 1500 volumes in various scientific fields related to agriculture. Some professional journal holdings in the same fields date back to 1959.

The U. S. Water Conservation Laboratory List of Publications, containing 1600 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications. Publication lists and most of the publications are available upon request.

During 1991, Current Contents, a disciplinary listing of new publications, was made available to the staff on the Local Area Network (LAN).

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[1] Appendix A lists manuscripts published or formally accepted for publication in 1991.

MACHINE SHOP

C. L. Lewis, Machinist

The machine shop, staffed by one machinist, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U. S. Water Conservation Laboratory research projects. Following are examples of work orders completed in 1991:

> Fabricated acrylic plastic brackets and mounted inside a portable photosynthesis chamber to permit levelling a light sensor from outside the chamber whenever the chamber was relocated (see Garcia *et al.*, "The Influence of CO_2 Enrichment on Canopy Photosynthesis of Cotton," p. 50 in this report).
>
> Constructed two transportable devices for bidirectional reflectance and radiance measurements. Each device was capable of holding an exotech 4-channel radiometer and an infrared thermometer 3 meters above a surface and viewing the same 80-cm diameter target from look angles of 45 degrees either side of nadir, at 5-degree intervals. The devices had to be lightweight, with no part exceeding 1 meter in length, to allow transport as personal luggage aboard international commercial air carriers. The devices were used in the Orgeval experiment near Coulommiers, France (see Clarke and Moran, "Integration of Optical and Thermal Radiometry with Down-Looking Radar for Surface Water and Energy Flux Evaluation: An International Cooperative Experiment," p. 68 in this report); the HAPEX Sahel Experiment in Niger, West Africa, the SPOT II satellite calibrations at White Sands Missile Range, New Mexico, and in the MAC BRF experiment (see Clarke, et al., "Aircraft-Based Bidirectional Reflectance of Agricultural Targets," p. 69 in this report).
>
> Fabricated, from circular metal rods, the frameworks for 200 shading stands to protect young saguharo cacti from the direct rays of the sun in a long-term CO_2 enrichment experiment (see Idso and Kimball, "CO_2 Enrichment of Trees," p. 58 in this report).

Equipment purchases enhanced machine shop support capabilities: the milling machine and drill press, both over twenty-five years old, were replaced, and a surface grinder was added. The latter will make it possible to better fabricate items from hardened steel, from different types of steel, and with greater accuracy.

APPENDIX A

Manuscripts Published or Accepted for Publication in 1991

APPENDIX A

1. ALLEN, S.G., IDSO, S.B. and KIMBALL, B.A. 1990. Interactive effects of CO_2 environment on net photosynthesis of water lily. Agric. Ecosystem & Environ. 30:81-88. 5344-11130-001-00D

2. AMTHOR, J.S. and MCCREE, K.J. 1990. Carbon balance of stressed plants: A conceptual model for integrating research results. p. 1-15 IN: R. G. Alscher and J. R. Cumming (eds.) Stress Response in Plants: Adaptation Mechanisms. Wiley-Liss, Inc., New York. 5344-11130-004-00D

3. BALLING, R.C., JR. and IDSO, S.B. 1990. Confusing signals in the climatic record. Atmos. Environ. 24A(7):1975-1977. 5344-13610-001-00D

4. BALLING, R.C., JR. and IDSO, S.B. 1990. One hundred years of global warming? Environ. Conserv. 17:165. 5344-13610-001-00D

5. BIGGAR, S.F., DINGUIRARD, M.C., GELLMAN, D.I., HENRY, P.J., Jackson, R. D., MORAN, M.S. and SLATER, P.N. 1991. Radiometric calibration of spot 2 HRV - A comparison of three methods. IN: Present. SPIE Symp., Proc. Soc. Photo-Opt. Instr., Orlando, FL, Apr. 1991, 1493:155-162. 5344-13610-001-00D

6. BOUWER, H. 1990. Agricultural chemicals and groundwater quality. J. Soil & Water Conser. 45(2):184-189. 5344-13000-002-00D

7. BOUWER, H. 1990. Effect of groundwater depth on seepage into or out of channels and lakes. p. 1-24 IN: David L. Kirchner (eds.) Water Quality and Quantity Issues into the 1990's...Adaption to Current Realities. Proc. the Arizona Hydrological Soc. Second Annual Symp., Casa Grande, AZ, 14-16 Sep. 1989, 5344-13000-002-00D

8. BOUWER, H. 1990. Groundwater recharge with sewage effluent. Water Sci. Tech., 23:2099-2108 IN: W.G., K. J. Ives, D. Jenkins, H. Kroiss, A. C. Di Pinto, M. Suzuki, D. F. Toerien, A. Milburn, E. J. Izod and P. T. Nagle P. Grau (eds.) Water Pollution Research and Control. Proc. Fifth Biennial Conf., Kyoto, Japan, 29 Jul.-3 Aug. 1990. 5344-13000-002-00D

9. BOUWER, H. 1991. Groundwater recharge with wastewater. p. 113-119 IN: Proc. Nat. Conf. Irrig. and Drain. Eng., ASCE, Honolulu, HI, 22-26 Jul. 1991. 5344-13000-002-00D

10. BOUWER, H. 1991. Groundwater recharge with wastewater: Pre-and post-treatment. p. 1-11 IN: Challenges of the 1990's. Proc. Fifth Biennial Symp. on Artificial Recharge of Groundwater, Tucson, AZ, 29-31 May 1991. 5344-13000-002-00D

11. BOUWER, H. 1991. Role of groundwater recharge in treatment and storage of wastewater for reuse. Wat. Sci. Tech. Proc. the Int. Symp. on Wastewater Reclamation and Reuse, IAWPRC, Castell Platja d'Aro, Costa Brava, Spain, 24-26 Sep. 1991, 24(9):295-302. 5344-13000-002-00D.

12. BOUWER, H. 1991. Role of soil-aquifer treatment in water reuse. p. 738-746 IN: Peter A. Krenkel (eds.) Proc. 1991 Specialty Conf., Env. Engr. Div., ASCE, Reno, NV, 8-10 Jul. 1991. 5344-13000-002-00D

13. BOUWER, H. 1991. Simple derivation of the retardation equation and application to preferential flow and macrodispersion. Ground Water. 29(1):41-46. 5344-13000-002-00D

14. BOUWER, H. 1991. Treating sewage for irrigation and drinking. p. 53-62 IN: J. B. Summers and D. G. Leslie (eds.) Can Irrigated Agriculture Survive the Groundwater Crisis? U. S. Committee on Irrig. and Drain. Proc. 1991 Regional Mtg., El Paso, TX, 31 Jan.-2 Feb. 1991.

15. CLEMMENS, A.J. 1991. A direct solution to the surface irrigation advance inverse problem. J. Irrig. and Drain. Engr. 117(4):578-594. 5344-13000-001-00D

16. CLEMMENS, A.J. Discussion: Rational approach for modifying rotational water delivery schedule. Irrig. & Drain. Div. ASCE. (Accepted by Jrl. 15 Apr. 1991). 5344-13000-005-00D

17. CLEMMENS, A.J. Feedback control of a basin irrigation system. J. Irrig. and Drain. Engr. (Accepted by Jrl. 1991.). 5433-13000-001-00D

18. CLEMMENS, A.J. 1991. Irrigation uniformity relationships for irrigation system management. J. Irrig. and Drain. Engr. 117(5):582-699. 5344-13000-001-00D

19. CLEMMENS, A.J. and BOS, M.G. Critical depth relations for flow measurement design. J. Irrig. and Drain. Engr. (Accepted by Jrl. 7 Oct. 1991). 5344-13000-005-00D

20. CLEMMENS, A.J. et al., 1991. Contributing author to: Management, Operation and Maintenance of Irrigation and Drainage Systems, ASCE. W.R. Johnston and J.B. Robertson (eds.). 432 pp. 5344-13000-001-00D

21. CLEMMENS, A.J., HOLLY, F.M., BURT, C.M. and DEVRIES, J.J. 1991. Future needs for unsteady flow canal models. p. 501-507 IN: Proc. Nat. Conf. Irrig. and Drain. Eng., ASCE, Honolulu, HI, 22-26 Jul. 1991. 5344-13000-001-00D

22. CLEMMENS, A.J., HOLLY, F.M. and SCHUURMANS, W. 1991. Description and evaluation of program: Duflow. p. 418-424 IN: Proc. Nat. Conf. Irrig. and Drain. Eng., ASCE, Honolulu, HI. 22-26 Jul. 1991. 5344-13000-001-00D

23. CLEMMENS, A.J. and KEATS, J.B. Bayesian inference for feedback control: Theory. J. Water Resources Plan. and Mgmt. (Accepted by Jrl. 1991). 5344-13000-001-00D

24. CLEMMENS, A.J. and KEATS, J.B. Bayesian statistics for feedback control: Surface irrigation parameter estimation. J. Water Resources Plan. and Mgmt. (Accepted by Jrl. 1991). 5344-13000-001-00D

25. CLEMMENS, A.J., WALKER, W.R. and GOOCH, R.S. 1991. Irrigation canal system unsteady flow modeling. p. 231-237 IN: Proc. Nat. Conf. Irrig. and Drain. Eng., ASCE, Honolulu, HI, 22-26 Jul. 1991. 1991. 5344-13000-001-00D

26. DEDRICK, A.R. 1991. Surface-drained level basins for rice production. p. 129-137 IN: Proc. Nat. Conf. Irrig. and Drain. Eng., ASCE, Honolulu, HI, 22-26 Jul. 1991. 1991. 5344-13000-001-00D

27. DIERIG, D.A. and BACKHAUS, R.A. 1990. Effect of morphactin and (DCPTA) on stem growth and bioinduction of rubber in guayule. HORTSCI. 25(5):531-533. 5344-21410-001-00D

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